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Modeling carbon regulation policies in inventory decisions of a multi-stage green supply chain: A game theory approach

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ABSTRACT

Governments and policymakers around the world put their best efforts to control the pollutions and climate change. Thus, they set various regulations to reduce greenhouse gases and carbon footprints. It is expected that firms should follow these regulations while maintaining their profitability. In this regard, firms can manage their carbon emissions across their supply chain (SC) by inventory management, since operational adjustments may affect the amount of carbon emissions, such as changing the production quantity and the frequency of transportations. This study applies a Stackelberg game between the government and a multi-stage green supply chain (GSC), in which the government's goal is to maximize social welfare and that of the GSC is to minimize its cost. First, we formulate the inventory cost and carbon emission of a multi-stage GSC under two decision-making structures: non-coordinated and coordinated GSCs. Second, we develop eight bi-level mathematical programming models considering the structure of the GSC and the regulations of the government including carbon cap, carbon tax, carbon trade, and carbon offset. Then two solution approaches will present for solving problems based on the type of the GSC structure. This study examines the effect of coordination and carbon regulations on inventory cost, carbon emission and the objective function of the government.

1. Introduction

The concurrent development of industries and environment has become a new challenge in the world. The emission of greenhouse gases (GHGs), especially carbon, from industrial activities is one of the main issues for the environment and is the primary cause of global warming (Stern, 2006). In recent years, the regulators and governments have paid significant attention to this problem. Consequently, many policies and regulations have formulated. For instance, the Kyoto Protocol had ratified in an international treaty, and as a result, a cap-and-trade system had been established. According to this system, a firm may sell its excess emission from the assigned amount units through the emission trading market. An emission trading system (ETS) is an incentive policy instrument for managing the emission of GHGs (Du, Ma, Fu, Zhu, & Zhang, 2015). Moreover, policymakers have developed other plans to reduce the emission of carbon. For example, the US EPA established carbon emission allowance for power plants at the national level (Kuo, Hong, & Lin, 2016), and some countries such as Australia implemented the carbon taxation scheme (Zakeri, Dehghanian, Fahimnia, & Sarkis, 2015).

In order to meet the requirements of governments, companies require managing their environmental impacts and wastes among all stages of their supply chain (SC) while maintaining the profitability. In this area, firms need to integrate decisions in their strategic plan and evaluate them on a continuous basis, as various methods have developed in the literature to determine performance rate of organization strategies (see Sobhanallahi, Gharaei, & Pilbala, 2016a, 2016b). However, the companies seem more interested in increasing their profits rather than investing in carbon footprint reduction, and thus reducing the emission of carbon has become a critical challenge for companies and governments (Zhao, Liu, Zhang, & Huang, 2017). The green supply chain management (GSCM) can help companies to save energy, reduce pollution and continuously do their business by considering environmental impact and resource efficiency (Hu & Li, 2011). Therefore, integrating green policies with inventory and production systems is vital for business success (Gharaei, Karimi, & Shekarabi, 2018; Gharaei, Pasandideh, & Akhavan Niaki, 2018). A firm needs to manage its carbon footprint across the SC to meet the governments' regulations. Various methods can deploy in the GSCM to reduce carbon footprints such as redesigning the product or packaging, using new technologies in manufacturing, and using efficient vehicles for product delivery. Meanwhile, many studies showed that inventory management could be very effective for the reduction of carbon emission (see Bouchery, Ghaffari, Jemai, & Dallery, 2012; Chen & Monahan, 2010; Hovelaque &

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Bironneau, 2015). The inventory policy of a firm determines variables which may affect the emission of carbon such as a number of deliveries, order or production quantities and storage amount. As a result, a firm can reduce its emission by operational adjustment and defining environmental inventory policies.

The carbon regulations and the need for profitability of companies will make the interaction between the government and SCs. Therefore, in this study, we formulate this interaction by game theory approach. The government imposes a regulation to control the emission of carbon and a green supply chain (GSC) requires to minimize its chain-wide costs and comply with the requirements of the government. Hence, there is a trade-off between the total cost of the GSC and the amount of the emission of carbon under governmental regulations.

In the real world, a producer may use several players in its SC to release a product to market. An efficient management should consider the complete end-to-end process such as design, procurement, production planning, distribution, and fulfillment (Gharaei & Pasandideh, 2016). In this regard, we consider a multi-stage GSC that there is a manufacturer in its center and contains a number of suppliers, distributors, and retailers. These members incur ordering, transportation, production, and inventory holding costs. Two different structures are applied to the GSC. In the first structure, the members use a coordination mechanism to manage the flow of the products as a centralized network, which is called the coordinated GSC. In the second structure, the members make their decisions separately, which is called the non-coordinated GSC.

On the other hand, in this study, on the reduction of carbon emission, we examine four different regulations, namely carbon cap, carbon tax, carbon trade, and carbon offset, which the government sets them. In the carbon cap framework, the amount of carbon that emitted by a GSC should be less than a certain cap. In a carbon tax scheme, the government determines tax per unit of carbon emission as a penalty for the GSC. According to the carbon trade or the cap-and-trade policy, each carbon emitter can gain an allowance, that is, if firms produce carbon more than their allowance, they should purchase emission from the market as a penalty, but if firms generate carbon less than their allowance, they can sell their surplus emission and gain revenue. Therefore, it is an incentive system to encourage companies in environmental efforts (Zakeri et al., 2015). The last scheme is the carbon offset or the cap-and-offset, in which specific caps are imposed on an emitter and just excess emission is penalized by purchasing emission credits (Schapiro, 2010). Each of these regulations can influence the optimal solution of the GSC in a different way. We propose different mathematical models to examine how firms managing their inventories under each regulation.

By applying the above-mentioned regulations and the structure of the GSC to the problem, the Stackelberg game has found to be a useful tool for formulating interaction between the government and the GSC. The fundamental research questions are as follows:

1. How can the inventory cost and carbon emission of the multi-stage GSC be formulated?
2. How can different carbon emission regulations be modeled and can influence the optimal strategy between members?
3. What should be the Stackelberg equilibrium for these problems?

This paper is organized as follows. The literature is reviewed in Section 2. The assumptions of the problem are discussed in Section 3. The mathematical models of the problem are presented in Section 4. The solution approach described in Section 5. A numerical example for solving the models, exploring different methods, is presented in Section 6. Finally, the conclusion of the study is presented in Section 7.

2. Literature review

The literature is categorized into three parts. The first part reviews the researches that consider carbon footprints in inventory management. The second part analyzes the existing literature on games between SCs and governments and the third part presents the research gap and contributions of this study.

2.1. Inventory management considering the emission of carbon

In the past few years, the literature on carbon footprints in inventory management has increased considerably. In this field, one of the leading studies is reported by Benjaafar, Li, and Daskin (2013). They developed models that consider both inventory cost and carbon emission. They investigated the effect of different regulations, such as emission caps, taxes on emission, cap-and-offset, and cap-and-trade, on the basic inventory models. Similarly, a model that incorporates carbon emission parameters into the classical EOQ model developed by Hua, Cheng, and Wang (2011) and Chen, Benjaafar, and Elomri (2013). They found the optimal ordering quantity and emission under different carbon policies. Bouchery et al. (2012) proposed a multi-objective problem that integrates carbon emission criteria into an inventory model for a two-echelon SC. They proved that the operational adjustment is an effective way of reducing environmental impacts. Toptal, Özlü, and Konur (2014) studied the classical EOQ model under three different carbon regulations, where a retailer has the option to invest in carbon reduction. They showed that the cap-and-trade policy gives more motivation for green investment. Schaefer and Konur (2014) analyzed a multi-item inventory model under the carbon-cap regulation. They used a genetic algorithm to solve this problem. Bazan, Jaber, and Zanoni (2015) developed two models for coordination of a two-echelon SC with considering GHG emission under tax policy. They showed that vendor-managed inventory (VMI) model has more benefit for the SC economically than classical coordination model. Also, Jiang, Li, Qu, and Cheng (2016) presented a VMI model for a SC consist of one manufacturer and a supplier under a carbon trade scheme. They showed that the optimal solution of the manufacturer depends on the carbon emission parameter related to transportation. Pasandideh, Niaki, and Gharaei (2015) developed VMI problem for the single vendor-buyer problem and used sequential quadratic programming approach to find the optimal production quantity. Zakeri et al. (2015) examined the effect of the carbon trade and carbon tax schemes on the cost of an Australian SC. They showed that the carbon trade scheme is a better option to measure the performance of a SC. A carbon trade mechanism motivates companies to apply GSCM with financial incentives. Likewise, Ding, Zhao, An, and Tang (2016) showed that an incentive mechanism is more effective for reducing the pollutants that produced by a SC. Du et al. (2015) evaluated the optimal solution for the members of a two-echelon SC in a carbon trade system considering the Stackelberg game. Dye and Yang (2015) established an inventory replenishment model considering the deteriorating product and the trade credit condition under carbon trade and carbon offset policies. García-Alvarado, Paquet, Chaabane, and Amodeo (2017) proposed a model for optimal replenishment inventory with remanufacturing under the cap-and-trade scheme. They used a Markov decision process to solve this model. Ma, Ji, Ho, and Yang (2018) presented a mathematical model for determining the optimal production quantity and supplier selection in a SC consisting of a manufacturer and suppliers under the carbon tax scheme. Gurtu, Jaber, and Searcy (2015) examined the impact of increasing carbon tax on the total cost of a SC. They found that tax can reduce environmental impacts but changes optimal cost too. Chen, Wang, Kumar, and Kumar (2016) developed a newsvendor model under carbon trade scheme and analyzed the trade-off between costs and the carbon emission reduction by investing in the green technology. In another study, a model to manage order quantity and green investment simultaneously were proposed by Nematollahi, Hosseini-Motlagh, and Heydari (2017). Ghosh, Jha, and Sarmah (2017) considered a two-echelon SC that aims to minimize inventory cost under carbon cap policy. Bouchery, Ghaffari, Jemai, and Tan (2017) suggested an

inventory model for a two-echelon SC with carbon emission. They showed that coordination among SC members can reduce both the cost and emission. In another study, two coordination mechanisms studied for a two-echelon closed loop SC with considering GHG emission and energy usage by Bazan, Jaber, and Zanoni (2017). Tsao, Lee, Chen, and Liao (2017) studied a newsvendor problem considering carbon emission, trade credit, and product recycling under three different regulations including carbon cap, carbon tax, and carbon trade.

Some studies examined other criteria along with the inventory problem. Yi, Xue, and Zhimin (2014) applied a pricing variable into the problem and presented a model for ordering and pricing strategies in a two-echelon SC with a stochastic demand under the carbon-cap scheme. Similarly, Hovelaque and Bironneau (2015) investigated a joint inventory and pricing problem in a firm under the carbon tax and carbon trade regulations. Zheng, Liao, and Yang (2016) further developed this problem for an SC with a stochastic demand under carbon trade regulation. Moreover, Miao, Mao, Fu, and Wang (2018) formulated a pricing and production quantity problem of a manufacturer with remanufacturing under the carbon tax and carbon trade regulations. Some studies, considered carbon emission parameters in a joint SC design and inventory planning problem and developed a multi-objective optimization problem (Alhaj, Svetinovic, & Diabat, 2016; Jamshidi, Ghomi, & Karimi, 2012; Kannegiesser & Günther, 2014; Mallidis, Vlachos, Iakovou, & Dekker, 2014).

Given that in a real world, a SC may consist of more than two levels and should manage environmental aspects in its all stages. Gharaei and Pasandideh (2016) developed inventory model for multi-product and multi-stage production SC. Moreover, Gharaei and Pasandideh (2017a) developed inventory cost model for four-echelon SC and used sequential quadratic programming to find solutions. In another similar study, Gharaei, Pasandideh, et al. (2018) examined the inventory model of a multi-echelon SC with imperfect products. Hoseini Shekarabi, Gharaei, and Karimi (2018) developed an optimal lot-sizing policy for a multi-product, multi-stage, centralized SC and used a decomposition method for solving the problem. Although many other research works, such as Ben-Daya, As'ad, and Seliaman (2013), Gharaei and Pasandideh (2017b), Gharaei, Pasandideh, and Arshadi Khamseh (2017), Nikandish, Eshghi, and Torabi (2009), Zhang (2013) and Zhao, Wu, and Yuan (2016), studied inventory control in a multi-stage SC, but a few studies considered carbon emission parameters into the inventory model of a multi-stage GSC. Sarkar, Ganguly, Sarkar, and Pareek (2016) applied a coordination mechanism to a three-echelon SC and found the optimum inventory, production, and carbon emission cost. Huang, Wang, Zhang, and Pang (2016) established a Stackelberg game model in a three-echelon SC for optimizing inventory planning, product line design, supplier selection, and pricing with considering GHG emissions. They applied a genetic algorithm to find the optimal solution. Gharaei, Karimi, et al. (2018) developed a MINLP model for integrated multi-product and multi-buyer SC with considering quality inspection, VMI, and green policies under tax cost of GHG emissions. They proposed an OA/ER/AP algorithm to find the optimal solution of large-scale problems. The studies in this field are summarized and categorized in Table 1.

2.2. Game between the government and the supply chain

The regulators and governments all around the world impose different policies and instruments on firms in order to protect the environment and control global warming. These policies imply an interactive relationship between governments and companies. In this regard, game theory has found as a useful approach for modeling and analyzing this relationship. In this regard, some researchers developed a two-person game between the government and a firm with discrete strategies, in which the government may choose to inspect or penalize firms and the firms accordingly decide to implement green strategies (see Dayi & Jianwei, 2011; Kim, 2015; Shutao & Jiangao, 2011; Zhao, Neighbour, McGuire, & Deutz, 2013).

One of the first research studies that analyzed a game between the government and a SC at an operational planning level conducted by Sheu (2011). In which, a Nash bargaining model was presented to analyze competition between two SCs with reverse logistics under government financial intervention. According to that model, SCs aim to maximize their profit by determining the production quantity and price, and the government aims to maximize social welfare by determining tax and subsidy. Jin, Wang, and Mei (2011) developed a game model between the government and a SC and found the optimal solution for the production quantity, product price, and subsidy by maximizing social welfare. Sheu and Chen (2012) analyzed the effect of government intervention on two rival green SCs. They suggested that the combined use of the green taxation and subsidy strategy is more effective for the government rather than pure taxation scheme. Sheu and Gao (2014) examined the cooperation mechanism between the members of reverse SCs under tax and subsidy strategies of the government. They showed that cooperation could increase the profit of the firms and utility of the government.

In practice, the government usually is more powerful than SCs and therefore the Stackelberg game can be more suitable to characterize the interaction between them. Hafezalkotob (2015) developed a production and pricing game between the government and two regular and green SCs, which determines optimal pricing and tariffs under the revenue seeking and environmental protection policies of the government. In another similar study, Madani and Rasti-Barzoki (2017) presented a model for pricing, greening strategies, and tariffs in both centralized and decentralized GSCs. Hafezalkotob (2017) defined four policies, such as energy saving, revenue seeking, social welfare, and sustainable development, for the Stackelberg leader government. He evaluated the effect of each policy on a GSC with three different structures comprising competition, coopetition, and cooperation. Hong, Chu, Zhang, and Yu (2017) developed a Stackelberg model between a government and multiple firms under carbon trade scheme where each firm determines its production quantity and government determines the carbon cap and a target for carbon reduction. In addition, there are other studies in the field of carbon emission regulations that can be referred. Zhao, Neighbour, Han, McGuire, and Deutz (2012) adopted the game theory approach to analyze the optimal strategies for reducing material risk and carbon emission in a SC under governmental sanctions and incentives policies. Kuo et al. (2016) studied a Nash game between the government and a firm, in which the government aims to maximize social welfare by imposing carbon tax regulation and the firm aims to maximize its profit. Wu, Liu, and Xu (2017) established an evolutionary game for the reduction of carbon emission and adopted a simulation approach for solving the game model. Hafezalkotob (2018) studied a Stackelberg game between a government and two rival GSCs under different intervention policies for energy saving. Table 2 lists and categorizes the researches that developed game theory models for interaction between government and SC(s).

2.3. Research gap and contributions

Although several studies developed inventory models in a GSC, the review of the literature shows that only a few applied an inventory model in a multi-stage GSC with considering carbon emission parameters. On the other hand, to the best of our knowledge, no study has considered a game between the government and a multi-stage GSC aiming to optimize inventory cost and carbon emission policies.

Thus, in this study, two main contributions are presented to fill this research gap. First, we consider carbon emission parameters in the inventory model of a multi-stage GSC, and also apply the coordinated and non-coordinated structures to the GSC. Second, we formulate the objective of the government under four different regulations, namely carbon cap, carbon tax, carbon trade, and carbon offset, and we examine the effect of each regulation on the optimal decisions of the GSC.

Table 1
List of related studies in the inventory management under carbon regulations.

References	Model	Echelons	SC structure		Decision variables of the SC	Regulation			
			Centralized	Decentralized		Carbon cap	Carbon tax	Carbon trade	Carbon offset
Bazan et al. (2015)	MINLP	Two-echelon	×		• Production quantity • Replenishment cycle		×		
Bazan et al. (2017)	MINLP	Two-echelon	×		• Production quantity		×		
Benjaafar et al. (2013)	MILP	Multi-echelon	×	×	• Order quantity • Backorder quantity	×	×	×	×
Bouchery et al. (2012)	EOQ	Two-echelon	×		• Order quantity	×		×	
Chen et al. (2013)	EOQ	Single-echelon			• Order quantity	×	×	×	×
Chen et al. (2016)	NLP	Two-echelon		×	• Order quantity • Price			×	
Ding et al. (2016)	NLP	Two-echelon	×	×	• Production quantity	×			
Du et al. (2015)	NLP	Two-echelon		×	• Order quantity • Price			×	
García-Alvarado et al. (2017)	NLP	Two-echelon		×	• Production quantity			×	
Ghosh et al. (2017)	NLP	Two-echelon	×		• Order quantity	×			
Gurtu et al. (2015)	MINLP	Two-echelon	×		• Production quantity		×		
Hovelaque and Bironneau (2015)	EOQ	Single-echelon			• Order quantity • Price		×	×	
Hua et al. (2011)	EOQ	Single-echelon			• Order quantity			×	
Jiang et al. (2016)	EPQ	Two-echelon	×		• Production quantity			×	
Miao et al. (2018)	NLP	Single-echelon			• Production quantity • Price		×	×	
Toptal et al. (2014)	EOQ	Single-echelon			• Order quantity	×	×	×	
Tsao et al. (2017)	Newsvendor	Single-echelon			• Order quantity • Price • Credit period	×	×	×	
Zakeri et al. (2015)	MILP	Multi-echelon	×		• Order quantity • Warehouse selection		×	×	
Gharaei, Karimi, et al. (2018)	MINLP	Two-echelon	×		• Production quantity		×		
This paper	MINLP	Multi-echelon	×	×	• Replenishment cycles	×	×	×	×

As a result, we develop eight scenarios according to the structure of the GSC and government regulations. We comprehensively compare the effects of different governmental carbon regulations on coordinated and non-coordinated GSC.

3. Problem description

In this study, we consider a multi-stage GSC that operates under the carbon regulations of the government and delivers one type of product to the market. As shown in Fig. 1, at the first stage of the GSC, there are S suppliers, who supply raw materials and send them to a manufacturer. At the next stage, the manufacturer uses the raw materials at a constant rate to produce the finished products. Then, the finished products are delivered to distribution centers that are denoted by D, who transport products to R retailers. At the last stage of the GSC, each retailer receives the products from only one distributor and fulfills the demand of a customer. This study assumes a constant demand rate with zero lead-time, finite production rates, and the shortage is not allowed.

Each member of the GSC incurs the ordering, inventory holding, and transportation costs. In addition, the manufacturer incurs the production cost too. The objective of the GSC is to minimize its cost by determining the optimal inventory decisions. There are two approaches for the chain members to make their decisions. First, they can operate individually regardless of others performances (i.e., a decentralized SC). Second, they can use a coordination mechanism to manage the flow of products and production processes more efficiently and expect to reduce their costs (i.e., a centralized SC). Three methods for inventory coordination in a centralized three-echelon SC were presented by Khouja (2003). We used one of these mechanisms, in which the replenishment cycle at each stage is an integer multiplier of the replenishment cycle of the subsequent stage. This coordination mechanism used by several authors such as Huang, Huang, and Newman (2011), Zhang (2013) and Zhao et al. (2016). These two approaches in the decision making of chain members are called the non-coordinated and coordinated GSC.

Moreover, each firm in the GSC emits carbon according to its inventory management processes. For instance, each ordering cycle can generate carbon emission due to the weight of the empty vehicles used for order delivery and holding inventory generate carbon due to warehousing activities and electricity consumption of the warehouse equipment. In addition, delivering products and production can emit significant carbon mostly because of fuel consumption of the vehicles and manufacturing activities. This study assumes that the amount of carbon emission is linearly related to per ordering cycle, held in the inventory per unit time, per transportation cycle, and per unit produced. This approach to modeling the carbon emission is used in many studies (see Bouchery et al., 2017; Hovelaque & Bironneau, 2015; Kannegiesser & Günther, 2014; Schaefer & Konur, 2014; Toptal et al., 2014).

In addition, the government imposes one of the four carbon regulations, namely, carbon cap, carbon tax, carbon trade, and carbon offset, for managing the carbon footprints of the GSC. The government aims to maximize social welfare (SW) that incorporates the trade-off between the consumer surplus, the profit of the firms, government net revenue and environmental benefits (see Hafezalkotob, 2018; Hong et al., 2017; Sheu & Chen, 2012; Sheu & Gao, 2014). The interaction between the government and the GSC will evaluate by Stackelberg game theory, where, the government is a leader because of its authority and the GSC is a follower in decision making. We formulate the problem in eight scenarios based on the structure of the GSC and the type of

Table 2
List of related studies in the game between the government and the SC.

References	Government decision variables	GSC Green feature				Government objective			Game approach			
		Remanufacturing	Green product	Carbon emission control	Energy saving	Social welfare	Environmental protection	Revenue seeking	Evolutionary	Nash	Bargaining	Stackelberg
Hafezalkotob (2015)	• Tariff		×				×	×				×
Hafezalkotob (2017)	• Tariff				×	×	×	×				×
Hafezalkotob (2018)	• Target for energy saving • Tariff				×	×						×
Hong et al. (2017)	• Carbon cap • Emission reduction target			×		×						×
Jin et al. (2011)	• Subsidy	×				×				×		
Kuo et al. (2016)	• Carbon tax			×		×				×		
Madani and Rasti-Barzoki (2017)	• Subsidy • Tariff		×					×				×
Sheu (2011)	• Subsidy • Tariff	×				×					×	
Sheu and Chen (2012)	• Subsidy • Tax	×				×				×		
Sheu and Gao (2014)	• Subsidy • Tax	×				×					×	
Xie (2015)	• Threshold for energy saving				×	×						×
Zhao et al. (2012)	• Subsidy • Carbon tax			×						×		
This paper	• Carbon cap • Carbon tax • Carbon price			×		×						×

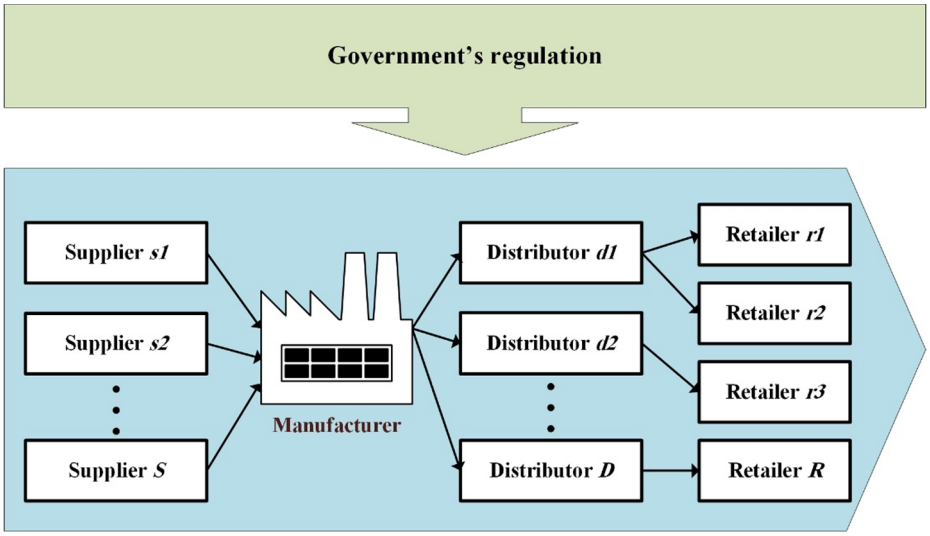

Fig. 1. Schematic view of a multi-stage GSC.

Decision making structure of the GSC

Government's regulation	Non-coordinated GSC	Coordinated GSC
Carbon cap	*Scenario 1*	*Scenario 5*
Carbon tax	*Scenario 2*	*Scenario 6*
Carbon trade	*Scenario 3*	*Scenario 7*
Carbon offset	*Scenario 4*	*Scenario 8*

Fig. 2. The government's regulations versus decision-making structures of the GSC.

government regulation that shown in Fig. 2.

In the next section, the mathematical models of inventory and carbon emission will discuss. Each scenario will develop as a bi-level programming problem. Then the solutions to achieve Stackelberg equilibrium will present.

4. The problem formulation

In this section, we first formulate the cost and the amount of carbon emission at each stage of the GSC. Then, the objective function of the government will formulate and finally, eight mathematical models will develop.

4.1. Notations

The parameters and decision variables of the mathematical models are listed in Table 3. We use the superscript index c to indicate coordinated GSC and its members (and related parameters) and n to refer non-coordinated ones.

4.2. The cost and carbon emission of retailers (Stage 4)

Retailers receive products from distributors and sell them in the market. It is evident that they incur ordering and holding costs. When there is no coordination between them, retailer r will order finished products from distributor d every cycle time, $T_{4,j}$. Based on the standard method for computing an economic order quantity, the total cost of the j^{th} retailer is:

$$IC_{4,j} = \frac{A_{4,j}}{T_{4,j}} + \frac{h_{4,j} D_{4,j} T_{4,j}}{2} \tag{1}$$

The inventory cost of all retailers in the non-coordinated GSC is:

$$IC_4^n = \sum_{j=r1}^{R} \left(\frac{A_{4,j}}{T_{4,j}} + \frac{h_{4,j} D_{4,j} T_{4,j}}{2}\right) \tag{2}$$

Under a coordination mechanism, all retailers order within a common cycle time T, hence the total cost of all retailers is:

$$IC_4^c = \sum_{j=r1}^{R} \left(\frac{A_{4,j}}{T} + \frac{h_{4,j} D_{4,j} T}{2}\right) \tag{3}$$

As stated in Section 3, the carbon emission of each firm in the GSC linearly associated with the frequency of delivery, the frequency of transportation, the average storage amount, and the production rate. Therefore, the total carbon emission of all retailers in the non-coordinated GSC is given by:

$$E_4^n = \sum_{j=r1}^{R} \left(\frac{e_{4,j}^o}{T_{4,j}} + e_{4,j}^h \frac{D_{4,j} T_{4,j}}{2}\right) \tag{4}$$

where the first term is the amount of emission because of the replenishment cycle and the second term is the amount of emission due to product holding that is obtained by multiplying the average inventory level and the related factor. Similarly, the carbon footprints of retailers in the coordinated GSC can be written as.

$$E_4^c = \sum_{j=r1}^{R} \left(\frac{e_{4,j}^o}{T} + e_{4,j}^h \frac{D_{4,j} T}{2}\right) \tag{5}$$

4.3. The cost and carbon emission of distributors (Stage 3)

The demand of each distributor is the sum of the orders of retailers which are supplied by the distributor. It means that if we consider that distributor dl supplies retailers $r1$ to R then, $D_{3,dl} = \sum_{j=r1}^{R} D_{4,j}$. When distributors operate separately, the inventory cost of the distributor dl is expressed as:

Table 3
The list of notations used to model the problem.

Parameters of the model:	
i	Index for the stage of the GSC, where $i = \{1, 2, 3, 4\}$ indicates suppliers, manufacturer, distributors and retailers respectively
r	Index for retailers, where $r = r1, r2, ...,R$
d	Index for distributors, where $d = d1, d2, ...,D$
m	Index for the manufacturer
s	Index for suppliers, where $s = s1, s2, ...,S$
j	Index for firms' number in each stage, where $j = \{r1, ...,R, d1, ...,D, m, s1, ...,S\}$
$D_{i,j}$	Demand rate of firm's j at stage i of the GSC
$A_{i,j}$	Fixed ordering cost per cycle time of firm's j at stage i of the GSC
$h_{i,j}$	Holding cost per unit of product per unit time of firm's j at stage i of the GSC
$b_{i,j}$	Fixed transportation cost per cycle time of firm's j at stage i of the GSC
S_m	Setup cost per cycle time of the manufacturer
h_w	Raw materials' holding cost per unit time of the manufacturer
$e^o_{i,j}$	Carbon emissions factor per replenishment's order of firm's j at stage i
$e^h_{i,j}$	Carbon emissions factor for holding inventory of firm's j at stage i
$e^t_{i,j}$	Carbon emissions factor per transportation cycle of firm's j at stage i
$e^P_{i,j}$	Carbon emissions factor per production quantity of firm's j at stage i
P_m	Manufacturer's production rate
β_s	The portion of raw material supplied by supplier s
$IC_{i,j}$	Inventory cost of firm's j at stage i of the GSC
IC^n_i	Inventory cost of all firms at stage i of the non-coordinated GSC
IC^c_i	Inventory cost of all firms at stage i of the coordinated GSC
IC^n	Inventory cost of the non-coordinated GSC
IC^c	Inventory cost of the coordinated GSC
$Z_{i,j}$	Total cost of firm's j at stage i of the GSC including inventory cost and carbon-related cost
Z^n_i	Total cost of all firms at stage i of the non-coordinated GSC including inventory cost and carbon-related cost
Z^c_i	Total cost of all firms at stage i of the coordinated GSC including inventory cost and carbon-related cost
Z^n	Total cost of the non-coordinated GSC including inventory cost and carbon-related cost
Z^c	Total cost of the coordinated GSC including inventory cost and carbon-related cost
E^n_i	Carbon emissions of all firms at stage i of the non-coordinated GSC
E^c_i	Carbon emissions of all firms at stage i of the coordinated GSC
E^n	Carbon emissions of the non-coordinated GSC
E^c	Carbon emissions of the coordinated GSC
GNR	The government net revenue
u_{gov}	Utility function of the government
Decision variables:	
$T_{i,j}$	Replenishment cycle time of firm's j at stage i in the non-coordinated GSC
T	Replenishment cycle time of retailers in the coordinated GSC
k_d	Integer multiplier of the cycle time for distributors
k_m	Integer multiplier of the cycle time for the manufacturer
k_w	Integer multiplier of the cycle time for raw materials
k_s	Integer multiplier of the cycle time for suppliers
C	Quantity of carbon for trading in carbon trade and carbon offset schemes
τ	The government tax per unit of carbon emission
p	The carbon price per unit in carbon trade and carbon offset schemes
cap	The government carbon cap

$$IC_{3,dl} = \frac{A_{3,dl}}{T_{3,dl}} + \frac{h_{3,dl} D_{3,dl} T_{3,dl}}{2} + \sum_{j=r1}^{R} h_{3,dl} T_{4,j} D_{4,j} + \sum_{j=r1}^{R} \frac{b_{3,dl}}{T_{4,j}} \tag{6}$$

The first and second terms above are the fixed ordering and holding costs, respectively. To avoid shortages, a distributor requires having enough inventory to satisfy all demands that if the retailers order at the same time altogether. The largest possible cumulative ordering size is $\sum_j T_{4,j} D_{4,j}$, therefore the third term in Eq. (6) is the holding cost to anticipate this largest order. The fourth term is the transportation cost per order. Therefore, the total cost of all distributors in the third stage of the non-coordinated GSC is:

$$IC^n_3 = \sum_{j=d1}^{D} \left(\frac{A_{3,j}}{T_{3,j}} + \frac{h_{3,j} D_{3,j} T_{3,j}}{2} + \sum_{r=r1}^{R} h_{3,j} T_{4,r} D_{4,r} + \sum_{r=r1}^{R} \frac{b_{3,l}}{T_{4,r}}\right) \tag{7}$$

In the coordinated GSC, all distributors have a common replenishment cycle that is an integer multiplier of T. This common replenishment cycle is $k_d T$. The inventory level of a coordinated GSC at each stage is shown in Fig. 3. As can be seen, the order quantity of distributor d is $D_d k_d T$, and the maximum inventory level of distributor d is $D_d T(k_d - 1)$. The average inventory of each distributor is calculated as:

$$\bar{I}^c_{3,j} = \frac{D_{3,j} T(k_d - 1)T + D_{3,j} T(k_d - 2)T + D_{3,j} T(k_d - 3)T + ... + D_{3,j} T^2}{k_d T} = \frac{D_{3,j} T(k_d - 1)}{2} \tag{8}$$

Therefore, the total cost of all distributors in a coordinated GSC is:

$$IC^c_3 = \sum_{j=d1}^{D} \left(\frac{A_{3,j}}{k_d T} + \frac{h_{3,j} D_{3,j} T(k_d - 1)}{2} + \frac{b_{3,j}}{T}\right) \tag{9}$$

Similar to the method that we used to calculate the carbon emission for retailers, we can calculate the emission produced by a distributor in both the coordinated and the non-coordinated GSC based on the ordering cycle, average inventory, and transportation cycle, which is expressed as follows:

$$E^n_3 = \sum_{j=d1}^{D} \left(\frac{e^o_{3,j}}{T_{3,j}} + e^h_{3,j} \frac{D_{3,j} T_{3,j}}{2} + \sum_{r=r1}^{R} e^t_{3,j} \frac{1}{T_{4,r}}\right) \tag{10}$$

$$E^c_3 = \sum_{j=d1}^{D} \left(\frac{e^o_{3,j}}{k_d T} + e^h_{3,j} \frac{D_{3,j} T(k_d - 1)}{2} + e^t_{3,j} \frac{1}{T}\right) \tag{11}$$

The first term of the Eqs. (10) and (11) represents the emission due to the ordering cycle. The second term is the emission for holding the inventory and the last term is the emission because of the transportation cycle.

4.4. The cost and carbon emission of the manufacturer (Stage 2)

In the second stage of the considered GSC, there is a manufacturer who has to fulfill the demand of all distributors i.e., $D_{2,m} = \sum_{j=d1}^{D} D_{3,j}$. The manufacturer receives raw materials from the suppliers and converts them into the finished product at a constant rate P_m. Although an integer multiplier between replenishment cycles has not used in the non-coordinated structure, in the manufacturing stage the inventory levels of the raw materials and the final products are synchronized by k_w. The total cost of the manufacturer in the non-coordinated GSC is:

$$IC^n_2 = \frac{S_m}{T_{2,m}} + \frac{h_{2,m} D_{2,m} T_{2,m}}{2}\left(1 - \frac{D_{2,m}}{P_m}\right) + \sum_{j=d1}^{D} h_{2,m} T_{3,j} D_{3,j} + \sum_{j=d1}^{D} \frac{b_{2,m}}{T_{3,j}} + \frac{A_{2,m}}{k_w T_{2,m}} + h_w \sum_{s=s1}^{S} \left(\frac{\beta_s D_{2,m} T_{2,m}}{2}\right)\left((D_{2,m}/P_m) + k_w - 1\right) \tag{12}$$

The first term in the above equation is the setup cost of the manufacturer per production cycle. The second term is the holding cost of the finished product. The average inventory is calculated based on the classical economic production quantity. The third term is the holding cost anticipating receiving orders of all distributors at the same time. The fourth term is the cost of transportation of the finished products to distributors. The fifth term is the fixed ordering cost for raw materials, and the sixth term is the holding cost for raw materials.

In the coordination mechanism, the production cycle of the manufacturer is an integer multiplier of the replenishment cycle of distributors. Therefore, the production cycle is $k_m k_d T$. The production quantity of the manufacturer is $D_{2,m} k_m k_d T$ per cycle and the production time is $(D_{2,m}/P_m) k_m k_d T$. As shown in Fig. 3, the number of the

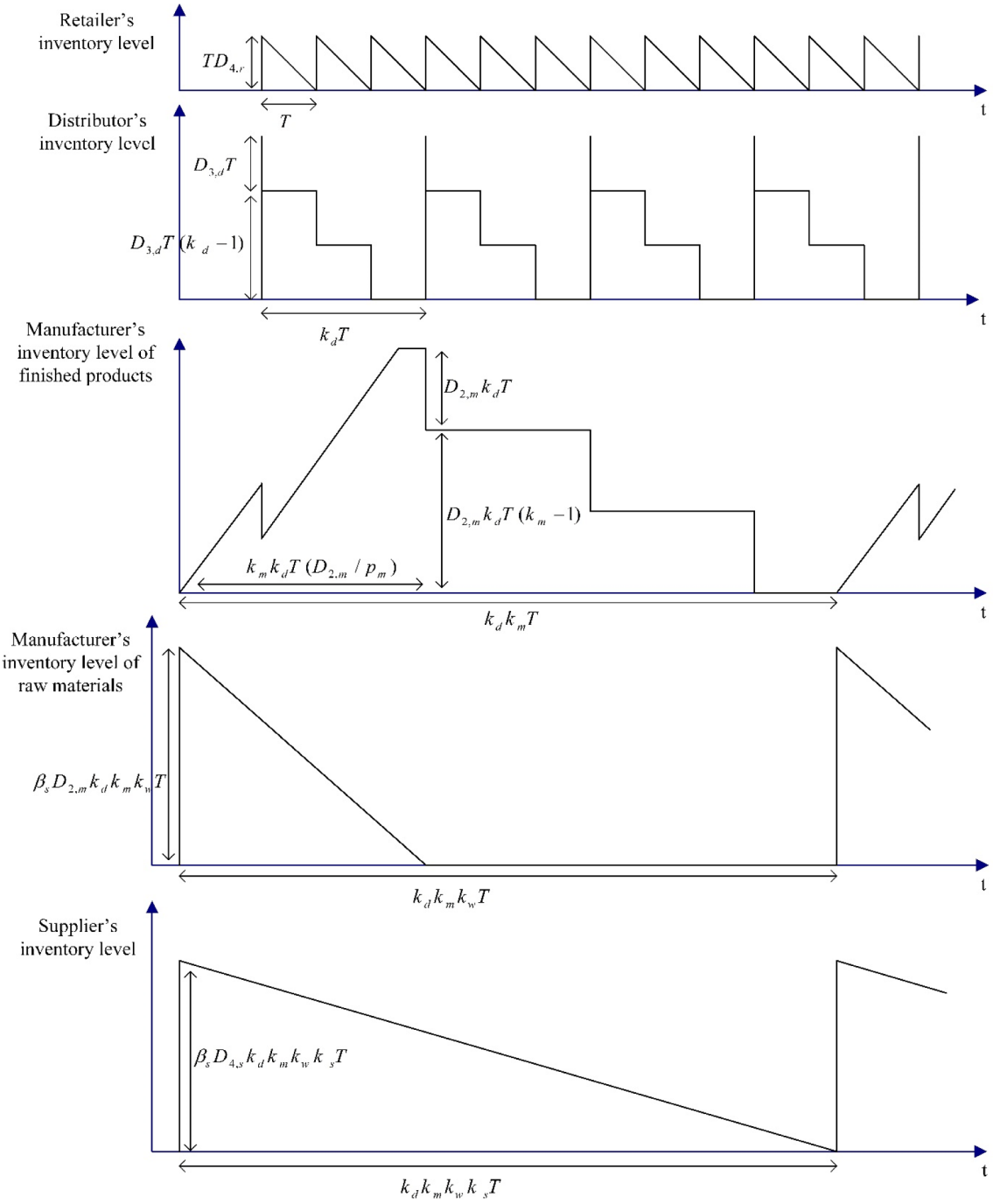

Fig. 3. Inventories behavior in each stage of the coordinated GSC where, $k_d = 3$, $k_m = 4$, $k_w = 1$ and $k_s = 1$.

remaining products after the production time is $D_{2,m}k_dT(k_m-1)$. Hence, the average inventory of the finished product can be calculated as follows.

$$\begin{aligned}\bar{I}_m^c &= \left(\frac{((D_{2,m}k_mk_dT)(D_{2,m}/P_mk_mk_dT)/2)}{k_mk_dT}\right)\\ &+\left(\frac{D_{2,m}k_dT(k_m-1)k_dT+D_{2,m}k_dT(k_m-2)k_dT+\ldots+D_{2,m}(k_dT)^2}{k_mk_dT}\right)\\ &=\left(\frac{(D_{2,m}k_dT)}{2}\left(\frac{k_mD_{2,m}}{P_m}\right)\right)+\left(\frac{D_{2,m}k_dT(k_m-1)}{2}\right)\\ &=\frac{(D_{2,m}k_dT)}{2}\left(k_m\frac{D_{2,m}}{P_m}+(k_m-1)\right)\end{aligned} \tag{13}$$

The manufacturer orders raw materials to supplier s with the amount of $\beta_sD_{2,m}$ at every cycle time $k_wk_mk_dT$ and uses them with rate P_m. The inventory level of raw materials depicted in Fig. 3. The average inventory of raw materials is calculated by the same method that we used in Eq. (13).

$$\begin{aligned}\bar{I}_w^c &= \left(\frac{(D_{2,m}/P_m)(k_mk_dT)\beta_sD_{2,m}k_wk_mk_dT}{2k_wk_mk_dT}+\right.\\ &\left.\frac{\beta_sD_{2,m}k_mk_dT(k_w-1)k_mk_dT+\beta_sD_{2,m}k_mk_dT(k_w-2)k_mk_dT+\ldots+\beta_sD_{2,m}(k_mk_dT)^2}{k_wk_mk_dT}\right)\\ &=\left(\frac{(D_{2,m}/P_m)(k_mk_dT)\beta_sD_{2,m}}{2}\right)+\left(\frac{\beta_sD_{2,m}k_mk_dT(k_w-1)}{2}\right)\\ &=\left(\frac{\beta_sD_{2,m}k_mk_dT}{2}\right)((D_{2,m}/P_m)+(k_w-1))\end{aligned} \tag{14}$$

Considering the average inventory of the finished products and raw materials, the total cost of the manufacturer under the coordination mechanism can be expressed as:

$$IC_2^c = \frac{S_m}{k_m k_d T} + \frac{h_{2,m} D_{2,m} k_d T}{2}\left(k_m \frac{D_{2,m}}{P_m} + k_m - 1\right) + \frac{b_{2,m}}{k_m k_d T} + \frac{A_{2,m}}{k_w k_m k_d T} + h_w\left(\frac{\beta_s D_{2,m} k_m k_d T}{2}\right)\left((D_{2,m}/P_m) + k_w - 1\right) \quad (15)$$

Carbon footprints of the manufacturer are formulated using the following equations in the non-coordinated and the coordinated GSC, respectively.

$$E_2^n = \frac{e_{2,m}^o}{T_{2,m}} + e_{2,m}^h\left[\left(\frac{D_{2,m} T_{2,m}}{2}\left(1 - \frac{D_{2,m}}{P_m}\right)\right) + \left(\frac{\sum_s \beta_s D_{2,m} T_{2,m}}{2}\right)\left((D_{2,m}/P_m) + k_w - 1\right)\right] + e_{2,m}^t \sum_{j=d1}^{D} \frac{1}{T_{3,j}} + e_{2,m}^p D_{2,m} T_{2,m} \quad (16)$$

$$E_2^c = \frac{e_{2,m}^o}{k_m k_d T} + e_{2,m}^h\left[\left(\frac{D_{2,m} k_d T}{2}\left(k_m \frac{D_m}{P_m} + k_m - 1\right)\right) + \left(\frac{\sum_s \beta_s D_{2,m} k_m k_d T}{2}\right)\left((D_{2,m}/P_m) + k_w - 1\right)\right] + e_{2,m}^t \frac{1}{k_m k_d T} + e_{2,m}^p D_{2,m} k_m k_d T \quad (17)$$

In the above equations, the first term is the amount of carbon that is emitted per setup cycle. The second term is the carbon emission because of inventory holding that is obtained by multiplying the average inventory of the finished products and the raw materials with its coefficient. Carbon emission rates may vary from one warehouse to another based on equipment and technology used. However, we assume that carbon emission rates are equal for the finished products and raw materials. The third term is the amount of emission related to transportation, and the final term is the amount of carbon that is emitted during the production time.

4.5. The cost and carbon emission of suppliers (Stage 1)

Each supplier supplies different kinds of raw materials required for the manufacturer. Thus, the quantity of the raw material that is supplied by supplier s per unit time is $\beta_s D_{2,m}$. Each supplier incurs the ordering cost, inventory holding cost and transportation cost for delivering raw materials to the manufacturer. In the non-coordinated structure, the total cost of the suppliers is:

$$IC_1^n = \sum_{j=s1}^{S}\left(\frac{A_{1,j}}{T_{1,j}} + \frac{h_{1,j} T_{1,j} \beta_s D_{2,m}}{2} + \frac{b_{1,j}}{k_w T_{2,m}}\right) \quad (18)$$

In the coordination structure, the replenishment cycle of all suppliers is a multiple integer of the manufacturer's replenishment cycle, $k_s k_w k_m k_d T$. From the inventory level of the suppliers that depicted in Fig. 3, it is evident that the average inventory of the suppliers is, $k_s k_w k_m k_d T \sum_s \beta_s D_{2,m}/2$ and the ordering cycle is, $1/k_s k_w k_m k_d T$. Thus, the cost of suppliers under the coordination mechanism is:

$$IC_1^c = \sum_{j=s1}^{S}\left(\frac{A_{1,j}}{k_s k_w k_m k_d T} + \frac{h_{1,j} k_s k_w k_m k_d T \beta_s D_{2,m}}{2} + \frac{b_{1,j}}{k_w k_m k_d T}\right) \quad (19)$$

Similar to previous stages, the carbon emission of suppliers in each structure obtained by multiplying the ordering cycle, average inventory, and transportation cycle in the relevant emission factors which are given by:

$$E_1^n = \sum_{j=s1}^{S}\left(\frac{e_{1,j}^o}{T_{1,j}} + e_{1,j}^h \frac{T_{1,j} \beta_s D_{2,m}}{2} + e_{1,j}^t \frac{1}{k_w T_{2,m}}\right) \quad (20)$$

$$E_1^c = \sum_{j=s1}^{S}\left(\frac{e_{1,j}^o}{k_s k_w k_m k_d T} + e_{1,j}^h \frac{k_s k_w k_m k_d T \beta_s D_{2,m}}{2} + e_{1,j}^t \frac{1}{k_w k_m k_d T}\right) \quad (21)$$

4.6. The model of a supply chain

When there is no coordination, the total cost of the multi-stage GSC is the summation of the costs of all members, which means the sum of Eqs. (2), (7), (12), and (18), and as a result, we have:

$$IC^n = IC_4^n + IC_3^n + IC_2^n + IC_1^n \quad (22)$$

The total carbon emission of the non-coordinated GSC is:

$$E^n = E_4^n + E_3^n + E_2^n + E_1^n \quad (23)$$

It is easy to see, that the total cost of the GSC in the coordinated scheme is the sum of Eqs. (3), (9), (15) and (19), which is given by:

$$IC^c = IC_4^c + IC_3^c + IC_2^c + IC_1^c \quad (24)$$

Moreover, the total carbon emission of the coordinated GSC is:

$$E^c = E_4^c + E_3^c + E_2^c + E_1^c \quad (25)$$

4.7. Modeling the regulations of the government

In the previous sections, we formulated both cost and carbon emission of the GSC. Now we define the objective function of the government in line with the social welfare (SW) maximization. Then, the problem under each regulation will develop. The SW can be defined as a trade-off between utility functions of the producers and environments. The first element of the SW is producer surplus, which is the summation of all firms' profit. Given that, as we have not considered the GSC income, instead of the GSC profit maximization, the cost minimization has been applied in the model of the government. The second element of the SW is the government revenue (GNR) that obtained through carbon taxes and the last element is environmental benefits. In this paper, the reduction in the total carbon emission of the GSC has considered as environmental benefits. Hence, the objective function of the government can be written as follow.

$$Min\ u_{gov} = (1 - \Omega)Z - \Omega GNR + \rho E \quad (26)$$

where the first term is producer surplus that increases by decreasing the total cost of the GSC. The second term is the revenue of the government that needs to be maximized. In the above equation, Ω is the trade-off between the cost of the GSC and the GNR that determined by the government. The range of this parameter can be $0 \leqslant \Omega \leqslant 1$. The last term in Eq. (26) shows environmental benefits, where $\rho \geqslant 0$ is the environmental importance factor from the point of view of the government. The low value of ρ indicates that the government considers economic objectives more than environmental objective and when ρ approaches to ∞, the government does not consider the benefit of the GSC and his revenue.

As described in Section 3, the government (Stackelberg leader) sets a regulation to control his concerns related to carbon emission and social welfare. As mentioned, four regulations are considered: carbon cap, carbon tax, carbon trade, and carbon offset. Each of these regulations is briefly described as follows.

A. In the carbon cap policy, the carbon emission of the GSC should not exceed a certain cap, which is determined by the government.
B. Under the carbon tax policy, the government penalizes the GSC according to the amount of emission by setting tax. This study assumes that tax is linearly associated per unit carbon.
C. In the carbon trade scheme that is also called cap-and-trade or cap-and-price, the government penalizes for emission that exceeds the specified cap. Moreover, in this scheme, the government encourages the firms that emit less than their cap and accordingly reward them.

Table 4
Bi-level mathematical models of the government and the GSC's for each scenario.

Regulation	Non-Coordinated GSC	Coordinated GSC
Carbon cap	$Min\ u_{gov}(cap) = (1-\Omega)Z^n + \rho E^n$ $Min\ Z^n = IC^n(T_{i,j}, k_w)$ $s.t.\ E^n \leqslant cap$ $Z^n \leqslant M_z$ $cap > 0$ $T_{i,j} > 0\ \forall\ i, j$ k_w is integer number	$Min\ u_{gov}(cap) = (1-\Omega)Z^c + \rho E^c$ $Min\ Z^c = IC^c(T, k_d, k_m, k_w, k_s)$ $s.t.\ E^c \leqslant cap$ $Z^c \leqslant M_z$ $cap > 0$ $T > 0$ k_d, k_m, k_w, k_s are integer numbers
Carbon tax	$Min\ u_{gov}(\tau) = (1-\Omega)Z^n - \Omega\tau E^n + \rho E^n$ $Min\ Z^n = IC^n(T_{i,j}, k_w) + \tau.\ E^n$ $Z^n \leqslant M_z$ $\tau > 0$ $T_{i,j} > 0\ \forall\ i, j$ k_w is integer number	$Min\ u_{gov}(\tau) = (1-\Omega)Z^c - \Omega\tau E^c + \rho E^c$ $Min\ Z^c = IC^c(T, k_d, k_m, k_w, k_s) + \tau.\ E^c$ $Z^c \leqslant M_z$ $\tau > 0$ $T > 0$ k_d, k_m, k_w, k_s are integer numbers
Carbon trade	$Min\ u_{gov}(p, cap) = (1-\Omega)Z^n + \rho E^n$ $Min\ Z^n = IC^n(T_{i,j}, k_w) + p.\ C$ $s.t.\ E^n - C = cap$ $\underline{c} \leqslant C \leqslant \bar{c}$ $Z^n \leqslant M_z$ $cap > 0$ $p > 0$ $T_{i,j} > 0\ \forall\ i, j$ k_w is integer number	$Min\ u_{gov}(p, cap) = (1-\Omega)Z^c + \rho E^c$ $Min\ Z^c = IC^c(T, k_d, k_m, k_w, k_s) + p.\ C$ $s.t.\ E^c - C = cap$ $\underline{c} \leqslant C \leqslant \bar{c}$ $Z^c \leqslant M_z$ $cap > 0$ $p > 0$ $T > 0$ k_d, k_m, k_w, k_s are integer numbers
Carbon offset	$Min\ u_{gov}(p, cap) = (1-\Omega)Z^n + \rho E^n$ $Min\ Z^n = IC^n(T_{i,j}, k_w) + p.\ C^+$ $s.t.\ E^n - C^+ = cap$ $Z^n \leqslant M_z$ $cap > 0$ $p > 0$ $T_{i,j} > 0\ \forall\ i, j$ k_w is integer number	$Min\ u_{gov}(p, cap) = (1-\Omega)Z^c + \rho E^c$ $Min\ Z^c = IC^c(T, k_d, k_m, k_w, k_s) + p.\ C^+$ $s.t.\ E^c - C^+ = cap$ $Z^c \leqslant M_z$ $cap > 0$ $p > 0$ $T > 0$ k_d, k_m, k_w, k_s are integer numbers

This scheme is implemented through a carbon trading market, where a firm can buy carbon if its amount of emission exceeds the carbon cap, or else a firm can sell its extra carbon credit and gain revenue.

D. Carbon offset or cap-and-offset is a policy where the government imposes the tax only on emission that exceeds a certain cap. In this setting, the government sets an emission cap but allows the GSC to reduce its emission by purchasing emission offsets through third parties.

Under the above regulations, the GSC (Stackelberg follower) makes its decisions about replenishment cycles. Based on the structure of the GSC and type of regulation, eight scenarios are developed. The mathematical models of each scenario are presented in Table 4. Generally, the Stackelberg problems show a hierarchical structure similar to a bi-level programming problem (BLPP). Each scenario is a bi-level mixed integer nonlinear problem (MINLP). Note, we consider that the government variables such as cap and tax are imposed on each firm of the GSC distinctly.

As can be seen in Table 4, in the carbon cap regulation (the first row of Table 4), the government determines cap at the top level of the model and at the lower level, the GSC determines replenishment cycles at each stage and also has a constraint for the amount of its carbon emission. In all scenarios, we define a constraint $Z \leqslant M_z$ as an individual rationality, where indicates that the GSC will continue its business if obtain a minimum utility.

In the models related to the carbon tax scheme (the second row of Table 4), the government at the top level problem determines tax per unit carbon, which will add to the GSC's costs at the lower level. In this scheme, the GNR obtained from the tax that multiplied by the amount of emission.

In the carbon trade and carbon offset schemes, the government determines a cap and carbon price and the GSC trade its emission at price p. The carbon price can consider either exogenous or endogenous. However, because the carbon trade market is more powerful than the companies, we assume that the carbon price is exogenous and determined by the government. At the top level problem of the carbon trade models (the third row of Table 4), the government determines cap and carbon price. Then at the lower level problem, the GSC transfer the carbon quantity C to the market at price p. The positive value C indicates the amount of carbon purchased from the trading market and the negative value C indicates the amount of carbon sold in the market. In this scheme the constraint $E - C = cap$ shows the carbon balance, if $E > cap$ the GSC must buy C units of carbon from the trading market, also if $E \leqslant cap$, the value of C is negative and the GSC can sell C units of carbon on the trading market and compensate part of its cost. Besides, the transferable carbon quantity C has a lower bound $\underline{c}$ and an upper bound $\bar{c}$. These boundaries determined by the amount of supply and demand for the carbon trading market. In the models related to the last regulation (the fourth row of Table 4), the term $p.\ C$ will add to the GSC cost only when C is positive, i.e., $E > cap$.

5. Solution approach

We confront a hierarchical decision-making problem where a leader first makes his decisions at the top level and then the followers make their decisions according to the decision at the top level. In this section, we investigate the solution for each scenario distinctively. First, the non-coordinated scenarios are investigated and then the coordinated ones. We used different approaches to solve non-coordinated and coordinated scenarios. In this regard, we seek to prove convexity of the

Table 5
Single-level mathematical models for Scenarios 1–4.

Scenario 1:

$Min\ u_{gov}(cap) = (1-\Omega)Z^n + \rho E^n$

$s.t.\ E^n \leqslant cap$

$$T^*_{4,j} = \sqrt{\frac{2(A_{4,j} + b_{3,dl} + \lambda_{4,j}e^o_{4,j} + \lambda_{4,j}e^t_{3,dl})}{D_{4,j}(h_{4,j} + 2h_{3,dl} + \lambda_{4,j}e^h_{4,j})}}$$

$$T^*_{3,j} = \sqrt{\frac{2(A_{3,j} + b_{2,m} + \lambda_{3,j}e^o_{3,j} + \lambda_{3,j}e^t_{2,m})}{D_{3,j}(h_{3,j} + 2h_{2,m} + \lambda_{3,j}e^h_{3,j})}}$$

$$T^*_{2,m} = \sqrt{\frac{2(S_m + \lambda_{2,m}e^o_{2,m} + (A_{2,m} + b_{1,j} + \lambda_{2,m}e^t_{1,j})/k_w)}{D_{2,m}(h_{2,m}(1-\frac{D_{2,m}}{P_m}) + h_w\sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1) + \lambda_{2,m}e^h_{2,m}[1 - \frac{D_{2,m}}{P_m} + \sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1)] + 2\lambda_{2,m}e^p_{2,m})}}$$

$$T^*_{1,j} = \sqrt{\frac{2(A_{1,j} + \lambda_{1,j}e^o_{1,j})}{\beta_s D_{2,m}(h_{1,j} + \lambda_{1,j}e^h_{1,j})}}$$

$Z^n \leqslant M_z$

$cap,\ T_{i,j} > 0,\ k_w$ is integer number

$\lambda_{1,j} \geqslant 0 \forall\ i, j$

Scenario 2:

$Min\ u_{gov}(\tau) = (1-\Omega)Z^n - \Omega\tau E^n + \rho E^n$

$$s.t.\ T^*_{4,j} = \sqrt{\frac{2(A_{4,j} + b_{3,dl} + \tau(e^o_{4,j} + e^t_{3,dl}))}{D_{4,j}(h_{4,j} + 2h_{3,dl} + \tau e^h_{4,j})}}$$

$$T^*_{3,j} = \sqrt{\frac{2(A_{3,j} + b_{2,m} + \tau(e^o_{3,j} + e^t_{2,m}))}{D_{3,j}(h_{3,j} + 2h_{2,m} + \tau e^h_{3,j})}}$$

$$T^*_{2,m} = \sqrt{\frac{2(S_m + \tau e^o_{2,m} + (A_{2,m} + b_{1,j} + \tau e^t_{1,j})/k_w)}{D_{2,m}(h_{2,m}(1-\frac{D_{2,m}}{P_m}) + h_w\sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1) + \tau e^h_{2,m}[1 - \frac{D_{2,m}}{P_m} + \sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1)] + 2\tau e^p_{2,m})}}$$

$$T^*_{1,j} = \sqrt{\frac{2(A_{1,j} + \tau e^o_{1,j})}{\beta_s D_{2,m}(h_{1,j} + \tau e^h_{1,j})}}$$

$Z^n \leqslant M_z$

$\tau,\ T_{i,j} > 0,\ k_w$ is integer number

Scenario 3:

$Min\ u_{gov}(p, cap) = (1-\Omega)Z^n + \rho E^n$

$s.t.\ Z^n = IC^n(T_{i,j}, k_w) + p.\ C$

$$T^*_{4,j} = \sqrt{\frac{2(A_{4,j} + b_{3,dl} + (\lambda_{1,4,j} - \lambda_{2,4,j})(e^o_{4,j} + e^t_{3,dl}))}{D_{4,j}(h_{4,j} + 2h_{3,dl} + (\lambda_{1,4,j} - \lambda_{2,4,j})e^h_{4,j})}}$$

$$T^*_{3,j} = \sqrt{\frac{2(A_{3,j} + b_{2,m} + (\lambda_{1,3,j} - \lambda_{2,3,j})(e^o_{3,j} + e^t_{2,m}))}{D_{3,j}(h_{3,j} + 2h_{2,m} + (\lambda_{1,3,j} - \lambda_{2,3,j})e^h_{3,j})}}$$

$$T^*_{2,m} = \sqrt{\frac{2(S_m + \tau e^o_{2,m} + (A_{2,m} + b_{1,j} + (\lambda_{1,2,m} - \lambda_{2,2,m})e^t_{1,j})/k_w)}{D_{2,m}(h_{2,m}(1-\frac{D_{2,m}}{P_m}) + h_w\sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1) + (\lambda_{1,2,m} - \lambda_{2,2,m})e^h_{2,m}[1 - \frac{D_{2,m}}{P_m} + \sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1)] + 2(\lambda_{1,2,m} - \lambda_{2,2,m})e^p_{2,m})}}$$

$$T^*_{1,j} = \sqrt{\frac{2(A_{1,j} + (\lambda_{1,1,j} - \lambda_{2,1,j})e^o_{1,j})}{\beta_s D_{2,m}(h_{1,j} + (\lambda_{1,1,j} - \lambda_{2,1,j})e^h_{1,j})}}$$

$E^n - C = cap$

$\underline{c} \leqslant C \leqslant \bar{c}$

$\lambda_{1,i,j}(cap - E^n + C) = 0$

$\lambda_{2,i,j}(-cap + E^n - C) = 0$

$Z^n \leqslant M_z$

$cap,\ p,\ T_{i,j} > 0,\ k_w$ is integer number

$\lambda_{1,i,j},\ \lambda_{2,i,j} \geqslant 0 \forall\ i, j$

Scenario 4:

$Min\ u_{gov}(p, cap) = (1-\Omega)Z^n + \rho E^n$

$s.t.\ Z^n = IC^n(T_{i,j}, k_w) + p.\ C^+$

$$T^*_{4,j} = \sqrt{\frac{2(A_{4,j} + b_{3,dl} + (\lambda_{1,4,j} - \lambda_{2,4,j})(e^o_{4,j} + e^t_{3,dl}))}{D_{4,j}(h_{4,j} + 2h_{3,dl} + (\lambda_{1,4,j} - \lambda_{2,4,j})e^h_{4,j})}}$$

$$T^*_{3,j} = \sqrt{\frac{2(A_{3,j} + b_{2,m} + (\lambda_{1,3,j} - \lambda_{2,3,j})(e^o_{3,j} + e^t_{2,m}))}{D_{3,j}(h_{3,j} + 2h_{2,m} + (\lambda_{1,3,j} - \lambda_{2,3,j})e^h_{3,j})}}$$

(*continued on next page*)

Table 5 (*continued*)

$$T^*_{2,m} = \sqrt{\frac{2(S_m + \tau e^o_{2,m} + (A_{2,m} + b_{1,j} + (\lambda_{1,2,m} - \lambda_{2,2,m})e^t_{1,j})/k_w)}{D_{2,m}(h_{2,m}(1 - \frac{D_{2,m}}{P_m}) + h_w \sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1) + (\lambda_{1,2,m} - \lambda_{2,2,m})e^h_{2,m}[1 - \frac{D_{2,m}}{P_m} + \sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1)] + 2(\lambda_{1,2,m} - \lambda_{2,2,m})e^p_{2,m})}}$$

$$T^*_{1,j} = \sqrt{\frac{2(A_{1,j} + (\lambda_{1,1,j} - \lambda_{2,1,j})e^o_{1,j})}{\beta_s D_{2,m}(h_{1,j} + (\lambda_{1,1,j} - \lambda_{2,1,j})e^h_{1,j})}}$$

$$E^n - C^+ = cap$$

$$\lambda_{1,i,j}(cap - E^n + C) = 0$$

$$\lambda_{2,i,j}(-cap + E^n - C) = 0$$

$$Z^n \leqslant M_z$$

$cap,\ p,\ T_{i,j} > 0,\ k_w$ is integer number

$\lambda_{1,i,j},\ \lambda_{2,i,j} \geqslant 0\ \forall\ i, j$

objective function of the non-coordinated GSC as follows.

Proposition 1.. *The inventory cost function of the non-coordinated GSC, Eq. (22) is convex for over* $T_{i,j} > 0$ *and* $k_w \geqslant 1$.

See Appendix A for proof.

Proposition 2.. *The total carbon emission function of the non-coordinated GSC, Eq. (23) is convex for over* $T_{i,j} > 0$ *and* $k_w \geqslant 1$.

See Appendix B for proof.

According to Colson, Marcotte, and Savard (2007) when the problem of the follower at the lower level is convex and regular, it can be reformulated to a single level by replacing the Karush–Kuhn–Tucker (KKT) conditions of the lower level problem. Propositions 1 and 2 showed that the non-coordinated GSC problem is convex. Therefore, in the following, the KKT conditions of the GSC problem in Scenarios 1–4 are replaced and as a result, each scenario is converted into the equivalent single-level problem.

5.1. The non-coordinated GSC under carbon cap regulation (Scenario 1)

In this scenario, the non-coordinated GSC at the lower level problem aims to minimize his inventory cost and has a constraint where, $E^n \leqslant cap$. The KKT conditions of this problem are as follows.

$$\frac{\partial IC^n}{\partial T_{i,j}} + \lambda_{i,j}\frac{\partial E^n}{\partial T_{i,j}} = 0 \quad \forall\ i, j \tag{27}$$

$$E_{i,j} \leqslant cap \quad \forall\ i, j \tag{28}$$

$$\lambda_{i,j}(E_{i,j} - cap) = 0 \quad \forall\ i, j \tag{29}$$

$$cap,\ T_{i,j} > 0, \quad \lambda_{i,j} \geqslant 0 \tag{30}$$

where $\lambda_{i,j}$ is a multiplier associated with the KKT conditions and may consider as the shadow price for each constraint of the problem. By using Eq. (27), the best response strategies of the chain members can be obtained at each stage of the GSC as follows.

$$\frac{\partial IC^n}{\partial T_{4,j}} + \lambda_{4,j}\frac{\partial E^n}{\partial T_{4,j}} = \frac{-A_{4,j}}{T^2_{4,j}} + \frac{h_{4,j}D_{4,j}}{2} + D_{4,j}h_{3,dl} - \frac{b_{3,dl}}{T^2_{4,j}} + \lambda_{4,j}(\frac{-e^o_{4,j}}{T^2_{4,j}} + e^h_{4,j}\frac{D_{4,j}}{2} - e^t_{3,dl}\frac{1}{T^2_{4,j}}) = 0 \tag{31}$$

$$T^*_{4,j} = \sqrt{\frac{2(A_{4,j} + b_{3,dl} + \lambda_{4,j}e^o_{4,j} + \lambda_{4,j}e^t_{3,dl})}{D_{4,j}(h_{4,j} + 2h_{3,dl} + \lambda_{4,j}e^h_{4,j})}} \tag{32}$$

The above equation shows the optimal value for the retailers' replenishment cycle. The optimal solution for other stages of the GSC is computed as follows.

$$\frac{\partial IC^n}{\partial T_{3,j}} + \lambda_{3,j}\frac{\partial E^n}{\partial T_{3,j}} = \frac{-A_{3,j}}{T^2_{3,j}} + \frac{h_{3,j}D_{3,j}}{2} + h_{2,m}D_{3,j} - \frac{b_{2,m}}{T^2_{3,j}} + \lambda_{3,j}(\frac{-e^o_{3,j}}{T^2_{3,j}} + e^h_{3,j}\frac{D_{3,j}}{2} - e^t_{2,m}\frac{1}{T^2_{3,j}}) = 0 \tag{33}$$

$$T^*_{3,j} = \sqrt{\frac{2(A_{3,j} + b_{2,m} + \lambda_{3,j}e^o_{3,j} + \lambda_{3,j}e^t_{2,m})}{D_{3,j}(h_{3,j} + 2h_{2,m} + \lambda_{3,j}e^h_{3,j})}} \tag{34}$$

$$\frac{\partial IC^n}{\partial T_{2,m}} + \lambda_{2,m}\frac{\partial E^n}{\partial T_{2,m}} = \frac{-S_m}{T^2_{2,m}} + \frac{h_{2,m}D_{2,m}}{2}\left(1 - \frac{D_{2,m}}{P_m}\right) - \frac{A_{2,m}}{k_w T^2_{2,m}} + \frac{h_w \sum_s \beta_s D_{2,m}}{2}\left(\frac{D_{2,m}}{P_m} + k_w - 1\right) - \frac{b_{1,j}}{k_w T^2_{2,m}} + \lambda_{2,m}\left(\frac{-e^o_{2,m}}{T^2_{2,m}} + e^h_{2,m}\left[\left(\frac{D_{2,m}}{2}\left(1 - \frac{D_{2,m}}{P_m}\right)\right) + \left(\frac{\sum_s \beta_s D_{2,m}}{2}\right)\left(\frac{D_{2,m}}{P_m} + k_w - 1\right)\right] + e^p_{2,m}D_{2,m} - e^t_{1,j}\frac{1}{k_w T^2_{2,m}}\right) = 0 \tag{35}$$

$$T^*_{2,m} = \sqrt{\frac{2(S_m + \lambda_{2,m}e^o_{2,m} + (A_{2,m} + b_{1,j} + \lambda_{2,m}e^t_{1,j})/k_w)}{D_{2,m}(h_{2,m}(1 - \frac{D_{2,m}}{P_m}) + h_w \sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1) + \lambda_{2,m}e^h_{2,m}[1 - \frac{D_{2,m}}{P_m} + \sum_s \beta_s(\frac{D_{2,m}}{P_m} + k_w - 1)] + 2\lambda_{2,m}e^p_{2,m})}} \tag{36}$$

$$\frac{\partial IC^n}{\partial T_{1,j}} + \lambda_{1,j}\frac{\partial E^n}{\partial T_{1,j}} = \frac{-A_{1,j}}{T^2_{1,j}} + \frac{h_{1,j}\beta_s D_{2,m}}{2} + \lambda_{1,j}(\frac{-e^o_{1,j}}{T^2_{1,j}} + e^h_{1,J}\frac{\beta_s D_{2,m}}{2}) = 0 \tag{37}$$

$$T^*_{1,j} = \sqrt{\frac{2(A_{1,j} + \lambda_{1,j}e^o_{1,j})}{\beta_s D_{2,m}(h_{1,j} + \lambda_{1,j}e^h_{1,j})}} \tag{38}$$

We can rewrite the Scenario 1 to a single-level MINLP problem by replacing the optimal values of the replenishment cycles of the GSC into the upper-level problem. We list the single-level problems of each scenario in Table 5.

5.2. The non-coordinated GSC under carbon tax regulation (Scenario 2)

Under the carbon tax regulation, the non-coordinated GSC face an unconstrained problem where its total cost is $Z^n = TC^n + \tau.\ E^n$. To obtain the best response strategies of the GSC, the first order derivatives of Z^n with respect to each decision variable $T_{i,j}$, must satisfy the condition $\frac{\partial Z^n}{\partial T_{i,j}} = 0$. Thus, replenishment cycles of the GSC members regarding carbon tax can be found as follows.

$$\frac{\partial Z^n}{\partial T_{4,j}} = \frac{-A_{4,j}}{T_{4,j}^2} + \frac{h_{4,j}D_{4,j}}{2} + D_{4,j}h_{3,dl} - \frac{b_{3,dl}}{T_{4,j}^2} + \tau\left(\frac{-e_{4,j}^o}{T_{4,j}^2} + e_{4,j}^h\frac{D_{4,j}}{2} - e_{3,dl}^t\frac{1}{T_{4,j}^2}\right) = 0 \tag{39}$$

$$T_{4,j}^* = \sqrt{\frac{2(A_{4,j} + b_{3,dl} + \tau(e_{4,j}^o + e_{3,dl}^t))}{D_{4,j}(h_{4,j} + 2h_{3,dl} + \tau e_{4,j}^h)}} \tag{40}$$

$$\frac{\partial Z^n}{\partial T_{3,j}} = \frac{-A_{3,j}}{T_{3,j}^2} + \frac{h_{3,j}D_{3,j}}{2} + h_{2,m}D_{3,j} - \frac{b_{2,m}}{T_{3,j}^2} + \tau\left(\frac{-e_{3,j}^o}{T_{3,j}^2} + e_{3,j}^h\frac{D_{3,j}}{2} - e_{2,m}^t\frac{1}{T_{3,j}^2}\right) = 0 \tag{41}$$

$$T_{3,j}^* = \sqrt{\frac{2(A_{3,j} + b_{2,m} + \tau(e_{3,j}^o + e_{2,m}^t))}{D_{3,j}(h_{3,j} + 2h_{2,m} + \tau e_{3,j}^h)}} \tag{42}$$

$$\frac{\partial Z^n}{\partial T_{2,m}} = \frac{-S_m}{T_{2,m}^2} + \frac{h_{2,m}D_{2,m}}{2}\left(1 - \frac{D_{2,m}}{P_m}\right) - \frac{A_{2,m}}{k_w T_{2,m}^2} + \frac{h_w\sum_s \beta_s D_{2,m}}{2}\left(\frac{D_{2,m}}{P_m} + k_w - 1\right) - \frac{b_{1,j}}{k_w T_{2,m}^2} + \tau\left(\frac{-e_{2,m}^o}{T_{2,m}^2} + e_{2,m}^h\left[\left(\frac{D_{2,m}}{2}\left(1 - \frac{D_{2,m}}{P_m}\right)\right) + \frac{\sum_s \beta_s D_{2,m}}{2}\left(\frac{D_{2,m}}{P_m} + k_w - 1\right)\right] + e_{2,m}^p D_{2,m} - e_{1,j}^t\frac{1}{k_w T_{2,m}^2}\right) = 0 \tag{43}$$

$$T_{2,m}^* = \sqrt{\frac{2(S_m + \tau e_{2,m}^o + (A_{2,m} + b_{1,j} + \tau e_{1,j}^t)/k_w)}{D_{2,m}\left(h_{2,m}\left(1 - \frac{D_{2,m}}{P_m}\right) + h_w\sum_s \beta_s\left(\frac{D_{2,m}}{P_m} + k_w - 1\right) + \tau e_{2,m}^h\left[1 - \frac{D_{2,m}}{P_m} + \sum_s \beta_s\left(\frac{D_{2,m}}{P_m} + k_w - 1\right)\right] + 2\tau e_{2,m}^p\right)}} \tag{44}$$

$$\frac{\partial Z^n}{\partial T_{1,j}} = \frac{-A_{1,j}}{T_{1,j}^2} + \frac{h_{1,j}\beta_s D_{2,m}}{2} + \tau\left(\frac{-e_{1,j}^o}{T_{1,j}^2} + e_{1,j}^h\frac{\beta_s D_{2,m}}{2}\right) = 0 \tag{45}$$

$$T_{1,j}^* = \sqrt{\frac{2(A_{1,j} + \tau e_{1,j}^o)}{\beta_s D_{2,m}(h_{1,j} + \tau e_{1,j}^h)}} \tag{46}$$

Hence, the problem of Scenario 2 can be rewritten as presented in Table 5.

5.3. The non-coordinated GSC under carbon trade regulation (Scenario 3)

The objective function of the non-coordinated GSC in Scenario 3 is the minimization of $Z^n = TC^n + p.\,C$. This problem has a constraint, $E^n - C = cap$ that replaced by $E^n - C \leqslant cap$ and $-E^n + C \leqslant -cap$. As a result, the KKT conditions of the GSC problem in this scenario can be express as:

$$\frac{\partial Z^n}{\partial T_{i,j}} + \lambda_{1,i,j}\frac{\partial(E^n - C)}{\partial T_{i,j}} + \lambda_{2,i,j}\frac{\partial(-E^n + C)}{\partial T_{i,j}} = 0 \quad \forall\, i, j \tag{47}$$

$$E^n - C \leqslant cap \tag{48}$$

$$-E^n + C \leqslant -cap \tag{49}$$

$$\lambda_{1,i,j}(cap - E^n + C) = 0 \tag{50}$$

$$\lambda_{2,i,j}(-cap + E^n - C) = 0 \tag{51}$$

$$\underline{c} \leqslant C \leqslant \bar{c} \tag{52}$$

$$cap,\ p,\ T_{i,j} > 0, \quad \lambda_{1,i,j},\ \lambda_{2,i,j} \geqslant 0 \quad \forall\, i, j \tag{53}$$

The Eq. (47) is converted to $\partial Z^n/\partial T_{i,j} + (\lambda_{1,i,j} - \lambda_{2,i,j})\partial E^n/\partial T_{i,j} = 0$ and based on that we can compute each replenishment cycle similar to the previous section. As a result, the optimal values of the lower level problem are calculated and replaced into the government's problem as shown in Table 5.

5.4. The non-coordinated GSC under carbon offset regulation (Scenario 4)

Under the carbon offset scheme, if the carbon emission is more than a cap, i.e., $E^n > cap$, the C units of carbon transfer to the third party at price p, in this situation the problem mathematically can formulate similar to the carbon trade problem. Otherwise when $E^n \leqslant cap$, the value of C must equal zero, this situation mathematically can formulate similar to the carbon cap problem. Therefore, this scenario can be reformulated into a single-level MINLP as shown in Table 5.

To solve Scenarios 1–4, each problem from Table 5 is coded in GAMS software and solved by Baron solver.

Now, we present a solution for the coordinated GSC under each carbon regulation. The lower level problems of the Scenarios 5–8 contains five decision variables that one of them is continues (T) and four of them are integer (k_d, k_m, k_w, k_s). To solve these problems, we propose an algebraic method due to the difficulties related to the convexity of inventory cost function. This method used by several researchers such as Ben-Daya et al. (2013), Leung (2009), and Sarkar et al. (2016), that is developed in this paper to find the best response strategies of the GSC.

5.5. The coordinated GSC under carbon cap regulation (Scenario 5)

The objective function of the coordinated GSC in Scenario 5 is to minimize IC^c, that can be expressed as:

$$IC^c = \sum_{j=r1}^{R}\sum_{j=d1}^{D}\sum_{j=s1}^{S}\left(\frac{T}{2}\left[k_d\left(D_{2,m}(h_{3,j} - h_{2,m}) + k_m\left(\frac{h_{2,m}D_{2,m}^2}{P_m} + h_{2,m}D_{2,m} + h_w\beta_s D_{2,m}\left(\frac{D_{2,m}}{P_m} - 1\right) + h_w\beta_s D_{2,m}k_w + h_{1,j}k_s k_w\beta_s D_{2,m}\right)\right) + D_{2,m}(h_{4,j} - h_{3,j})\right] + \frac{1}{T}\left[\frac{1}{k_d}\left(A_{3,j} + \frac{1}{k_m}\left(S_m + b_{2,m} + \frac{A_{2,m} + b_{1,j}}{k_w} + \frac{A_{1,j}}{k_s k_w}\right)\right) + A_{4,j} + b_{3,j}\right]\right) \tag{54}$$

By changing variables, Eq. (54) can be simplified to:

$$IC^c = YT + \frac{X}{T} \tag{55}$$

See Appendix C for all values.

According to Eq. (55) the optimal replenishment cycle of the retailers and then optimal inventory cost can easily find as:

$$T^* = \sqrt{\frac{X}{Y}} \tag{56}$$

$$IC^{c*} = 2\sqrt{YX} \tag{57}$$

By expanding the terms of the Eq. (57), we can obtain each decision variable iteratively. The IC^{c*} rewrite as:

$$IC^{c*} = \sqrt{2}\sqrt{(k_d\omega + \alpha_1)\left(\frac{1}{k_d}\upsilon + \alpha_2\right)} \tag{58}$$

By using the perfect squares method, the above equation is transformed to:

$$IC^{c*} = \sqrt{2}\left\{\frac{1}{k_d}\left[k_d\sqrt{\omega\alpha_2} - \sqrt{\upsilon\alpha_1}\right]^2 + \left[\sqrt{\omega\upsilon} + \sqrt{\alpha_1\alpha_2}\right]^2\right\}^{1/2} \tag{59}$$

The optimal value of the k_d can be obtained when the other variables are fixed and the first term in above equation equal zero, i.e., $\left[k_d\sqrt{\omega\alpha_2} - \sqrt{\upsilon\alpha_1}\right]^2 = 0$. As a result, we have:

$$k_d^* = \sqrt{\frac{\upsilon\alpha_1}{\omega\alpha_2}} \tag{60}$$

The only term in Eq. (59) that contains the integer variable k_m is $\sqrt{\omega\upsilon}$. We have:

$$\sqrt{\omega\upsilon} = \sqrt{(\gamma_3 + k_m(\gamma_2 + k_w\gamma_1))\left(\sum_j A_{3,j} + \frac{1}{k_m}\left(\varphi_2 + \frac{1}{k_w}\varphi_1\right)\right)} = \left\{\frac{1}{k_m}\left[k_m\sqrt{(\gamma_2 + k_w\gamma_1)\sum_j A_{3,j}} - \sqrt{\left(\varphi_2 + \frac{1}{k_w}\varphi_1\right)\gamma_3}\right]^2 + \left[\sqrt{(\gamma_2 + k_w\gamma_1)\left(\varphi_2 + \frac{1}{k_w}\varphi_1\right)} + \sqrt{\gamma_3\sum_j A_{3,j}}\right]^2\right\}^{1/2} \tag{61}$$

Similar the way that we computed k_d, the optimal value of k_m is obtained by fixing values of other variables and setting the term $[k_m\sqrt{(\gamma_2 + k_w\gamma_1)\sum_j A_{3,j}} - \sqrt{(\varphi_2 + \frac{1}{k_w}\varphi_1)\gamma_3}]^2 = 0$ in the Eq. (61). As a result, we have:

$$k_m^* = \sqrt{\frac{(\varphi_2 + \frac{1}{k_w}\varphi_1)\gamma_3}{(\gamma_2 + k_w\gamma_1)\sum_j A_{3,j}}} \tag{62}$$

The optimal value for the variable k_w can be calculated by setting the term $\sqrt{(\gamma_2 + k_w\gamma_1)(\varphi_2 + \frac{1}{k_w}\varphi_1)} = 0$ from Eq. (61). Therefore, we have:

$$\sqrt{(\gamma_2 + k_w\gamma_1)(\varphi_2 + \frac{1}{k_w}\varphi_1)} = \{\frac{1}{k_w}[k_w\sqrt{\gamma_1\varphi_2} - \sqrt{\gamma_2\varphi_1}]^2 + [\sqrt{\gamma_1\varphi_1} + \sqrt{\gamma_2\varphi_2}]^2\}^{1/2} = 0 \tag{63}$$

$$k_w^* = \sqrt{\frac{\gamma_2\varphi_1}{\gamma_1\varphi_2}} \tag{64}$$

The term $\sqrt{\gamma_1\varphi_1}$ in the Eq. (63), contains the integer variable k_s. Thus, the last integer variable of the GSC problem k_s, can be obtained as follows.

$$\sqrt{\gamma_1\varphi_1} = \sqrt{\sum_j ((h_w\beta_s D_{2,m} + h_{1,j}k_s\beta_s D_{2,m})(A_{2,m} + b_{1,j} + \frac{A_{1,j}}{k_s}))} = \sum_j \left\{\frac{1}{k_s}[k_s\sqrt{h_{1,j}\beta_s D_{2,m}(A_{2,m} + b_{1,j})} - \sqrt{A_{1,j}h_w\beta_s D_{2,m}}]^2 + [\sqrt{h_{1,j}\beta_s D_{2,m}A_{1,j}} + \sqrt{h_w\beta_s D_{2,m}(A_{2,m} + b_{1,j})}]^2\right\}^{1/2} \tag{65}$$

$$k_s^* = \sqrt{\sum_j \frac{A_{1,j}h_w}{h_{1,j}(A_{2,m} + b_{1,j})}} \tag{66}$$

In the following subsections, we will calculate the best response strategies of the GSC in Scenarios 6–8 by using the method that described in this section. In the end, a comprehensive approach for solving problems of the coordinated GSC under each carbon regulation will present.

5.6. The coordinated GSC under carbon tax regulation (Scenario 6)

The total cost of the coordinated GSC under carbon tax regulation is $Z^c = IC^c + \tau E^c$. Similar to Section 5.5, we can simplify the inventory cost to $IC^c = YT + \frac{X}{T}$. Also, we can rewrite total emission as follows.

$$E^c = \sum_{j=s1}^{S}\sum_{j=d1}^{D}\sum_{j=r1}^{R}\frac{T}{2}[D_{2,m}e_{4,j}^h - D_3e_{3,j}^h + k_d(D_{2,m}e_{3,j}^h - D_{2,m}e_{2,m}^h + k_m(e_{2,m}^h D_{2,m}(\frac{D_{2,m}}{P_m} + 1) + e_{2,m}^h\beta_s D_{2,m}(\frac{D_{2,m}}{P_m} - 1) + 2e_{2,m}^p D_{2,m} + e_{2,m}^h\beta_s D_{2,m}k_w + e_{1,j}^h k_s k_w\beta_s D_{2,m}))] + \frac{1}{T}[e_{4,j}^o + e_{3,j}^t + \frac{1}{k_d}(e_{3,j}^o + \frac{1}{k_m}(e_{2,m}^o + e_{2,m}^t + \frac{e_{1,j}^t}{k_w} + \frac{e_{1,j}^o}{k_s k_w}))] \tag{67}$$

The above equation can be simplified to:

$$E^c = \hat{Y}T + \frac{\hat{X}}{T} \tag{68}$$

See Appendix D for all values.

The objective function of the GSC in this scenario rearrange as:

$$Z^c = IC^c + \tau.\ E^c = YT + \frac{X}{T} + \tau.\ (\hat{Y}T + \frac{\hat{X}}{T}) \tag{69}$$

We can find each decision variable of the coordinated GSC with regarding the government decision variable, i.e., carbon tax τ iteratively. By placing the first derivative of the Eq. (69) equal to zero, the optimal retailers' replenishment cycle and total cost are:

$$T^* = \sqrt{\frac{X + t\hat{X}}{Y + t\hat{Y}}} \tag{70}$$

$$Z^{c*} = Y\sqrt{\frac{X + t\hat{X}}{Y + t\hat{Y}}} + \frac{X}{\sqrt{\frac{X + t\hat{X}}{Y + t\hat{Y}}}} + t.\ (\hat{Y}\sqrt{\frac{X + t\hat{X}}{Y + t\hat{Y}}} + \frac{\hat{X}}{\sqrt{\frac{X + t\hat{X}}{Y + t\hat{Y}}}}) = 2\sqrt{(Y + t\hat{Y})(X + t\hat{X})} \tag{71}$$

The Eq. (71) expand as follows to calculate the optimal value of the integer variable k_d.

$$Z^{c*} = 2\sqrt{(Y + \tau\hat{Y})(X + \tau\hat{X})} = 2\sqrt{((\frac{k_d\omega + \alpha_1}{2}) + \tau(\frac{k_d\hat{\omega} + \hat{\alpha}_1}{2}))((\frac{\upsilon}{k_d} + \alpha_2) + \tau(\frac{\hat{\upsilon}}{k_d} + \hat{\alpha}_2))} = \sqrt{2}\sqrt{(k_d(\omega + \tau\hat{\omega}) + \alpha_1 + \tau\hat{\alpha}_1)(\frac{\upsilon + \tau\hat{\upsilon}}{k_d} + \alpha_2 + \tau\hat{\alpha}_2)} \tag{72}$$

By using the perfect squares method, the above equation is converted to:

$$Z^{c*} = \sqrt{2}\left\{\frac{1}{k_d}[k_d\sqrt{(\omega + \tau\hat{\omega})(\alpha_2 + \tau\hat{\alpha}_2)} - \sqrt{(\upsilon + \tau\hat{\upsilon})(\alpha_1 + \tau\hat{\alpha}_1)}]^2 + [\sqrt{(\omega + \tau\hat{\omega})(\upsilon + \tau\hat{\upsilon})} + \sqrt{(\alpha_1 + \tau\hat{\alpha}_1)(\alpha_2 + \tau\hat{\alpha}_2)}]^2\right\}^{1/2} \tag{73}$$

The optimal value of k_d will obtain by fixing other variables and setting $k_d\sqrt{(\omega + \tau\hat{\omega})(\alpha_2 + \tau\hat{\alpha}_2)} - \sqrt{(\upsilon + \tau\hat{\upsilon})(\alpha_1 + \tau\hat{\alpha}_1)} = 0$. As a result, we have:

$$k_d^* = \sqrt{\frac{(\upsilon + \tau\hat{\upsilon})(\alpha_1 + \tau\hat{\alpha}_1)}{(\omega + \tau\hat{\omega})(\alpha_2 + \tau\hat{\alpha}_2)}} \tag{74}$$

The only term that has variable k_m in the Eq. (73) is $\sqrt{(\omega + \tau\hat{\omega})(\upsilon + \tau\hat{\upsilon})}$ that can be expanded as follows.

$$\sqrt{(\omega + \tau\hat{\omega})(\upsilon + \tau\hat{\upsilon})} = \sqrt{(k_m(\gamma_2 + k_w\gamma_1 + \tau(\hat{\gamma}_2 + k_w\hat{\gamma}_1)) + \gamma_3 + \tau\hat{\gamma}_3)(\frac{1}{k_m}(\varphi_2 + \frac{1}{k_w}\varphi_1 + \tau(\hat{\varphi}_2 + \frac{1}{k_w}\hat{\varphi}_1)) + \sum_j A_{3,j} + \tau e_{3,j}^o)} = \left\{\frac{1}{k_m}\left[k_m\sqrt{(\gamma_2 + k_w\gamma_1 + \tau(\hat{\gamma}_2 + k_w\hat{\gamma}_1))(\sum_j A_{3,j} + \tau e_{3,j}^o)} - \sqrt{(\varphi_2 + \frac{1}{k_w}\varphi_1 + \tau(\hat{\varphi}_2 + \frac{1}{k_w}\hat{\varphi}_1))(\gamma_3 + \tau\hat{\gamma}_3)}\right]^2 + \left[\sqrt{(\gamma_2 + k_w\gamma_1 + \tau(\hat{\gamma}_2 + k_w\hat{\gamma}_1))(\varphi_2 + \frac{1}{k_w}\varphi_1 + \tau(\hat{\varphi}_2 + \frac{1}{k_w}\hat{\varphi}_1))} + \sqrt{(\gamma_3 + t\hat{\gamma}_3)(\sum_j A_{3,j} + \tau e_{3,j}^o)}\right]^2\right\}^{1/2} = 0 \tag{75}$$

By setting the first term of the above equation equal zero, the optimal value of k_m is:

Table 6
Input parameters for retailers.

j	$D_{4,j}$	$h_{4,j}$	$A_{4,j}$	$e_{4,j}^o$	$e_{4,j}^h$
r1	7500	30	110	0.7	0.2
r2	12,000	25	95	0.7	0.3
r3	10,000	35	90	0.75	0.3
r4	5500	30	100	0.65	0.2

Table 7
Input parameters for distributors.

j	$h_{3,j}$	$A_{3,j}$	$b_{3,j}$	$e^o_{3,j}$	$e^h_{3,j}$	$e^t_{3,j}$
d1	20	85	15	0.6	0.4	1.7
d2	24	90	14	0.6	0.4	1.8

Table 8
Input parameters for suppliers.

j	$h_{1,j}$	$A_{1,j}$	$b_{1,j}$	$e^o_{1,j}$	$e^h_{1,j}$	$e^t_{1,j}$
s1	7	70	18	0.5	0.4	1.6
s2	8	80	25	0.5	0.3	1.6
s3	8	75	22	0.6	0.3	1.4

$$k_m^* = \sqrt{\frac{(\varphi_2 + \frac{1}{k_w}\varphi_1 + \tau(\hat{\varphi}_2 + \frac{1}{k_w}\hat{\varphi}_1))(\gamma_3 + \tau\hat{\gamma}_3)}{(\gamma_2 + k_w\gamma_1 + \tau(\hat{\gamma}_2 + k_w\hat{\gamma}_1))(\sum_j A_{3,j} + \tau e^o_{3,j})}} \tag{76}$$

The third term of the Eq. (75) contains k_w, therefore we transform it algebraically and set it equal zero as follows.

$$\left\{\begin{array}{l}\frac{1}{k_w}[k_w\sqrt{(\gamma_1 + \tau\hat{\gamma}_1)(\varphi_2 + \tau\hat{\varphi}_2)} - \sqrt{(\varphi_1 + \tau\hat{\varphi}_1)(\gamma_2 + \tau\hat{\gamma}_2)}]^2 \\ +[\sqrt{(\gamma_1 + \tau\hat{\gamma}_1)(\varphi_1 + \tau\hat{\varphi}_1)} + \sqrt{(\gamma_2 + \tau\hat{\gamma}_2)(\varphi_2 + \tau\hat{\varphi}_2)}]^2\end{array}\right\}^{1/2} = 0 \tag{77}$$

$$k_w^* = \sqrt{\frac{(\varphi_1 + \tau\hat{\varphi}_1)(\gamma_2 + \tau\hat{\gamma}_2)}{(\gamma_1 + \tau\hat{\gamma}_1)(\varphi_2 + \tau\hat{\varphi}_2)}} \tag{78}$$

To obtain optimal value of the last integer variable k_s, we set the term $\sqrt{(\gamma_1 + \tau\hat{\gamma}_1)(\varphi_1 + \tau\hat{\varphi}_1)} = 0$ from Eq. (77).

$$\begin{aligned}&\sqrt{(\gamma_1 + \tau\hat{\gamma}_1)(\varphi_1 + \tau\hat{\varphi}_1)} = \\ &\sqrt{\sum_j (k_s\beta_s D_{2,m}(h_{1,j} + \tau e^h_{1,j}) + \beta_s D_{2,m}h_w + \tau\beta_s D_{2,m}e^h_{2,m})(\frac{A_{1,j} + \tau e^o_{1,j}}{k_s} + A_{2,m} + b_{1,j} + \tau e^t_{1,j})} \\ &= \sum_j \left\{\begin{array}{l}\frac{1}{k_s}\left[\begin{array}{l}k_s\sqrt{(\beta_s D_{2,m}h_{1,j} + \tau\beta_s D_{2,m}e^h_{1,j})(A_{2,m} + b_{1,j} + \tau e^t_{1,j})} \\ -\sqrt{(A_{1,j} + \tau e^o_{1,j})(\beta_s D_{2,m}h_w + \tau\beta_s D_{2,m}e^h_{2,m})}\end{array}\right]^2 \\ +\left[\begin{array}{l}\sqrt{(\beta_s D_{2,m}h_{1,j} + \tau\beta_s D_{2,m}e^h_{1,j})(A_{1,j} + \tau e^o_{1,j})} \\ +\sqrt{(\beta_s D_{2,m}h_w + \tau\beta_s D_{2,m}e^h_{2,m})(A_{2,m} + b_{1,j} + \tau e^t_{1,j})}\end{array}\right]^2\end{array}\right\}^{1/2} = 0\end{aligned} \tag{79}$$

$$k_s^* = \sqrt{\sum_j \frac{(h_w + \tau e^h_{2,m})(A_{1,j} + \tau e^o_{1,j})}{(h_{1,j} + \tau e^h_{1,j})(A_{2,m} + b_{1,j} + \tau e^t_{1,j})}} \tag{80}$$

5.7. The coordinated GSC under carbon trade regulation (Scenario 7)

In this scenario, the coordinated GSC seeks to minimize $Z^c = IC^c + p.\ C$ at the lower level problem. According to a constraint of this problem, where $E^c - C = cap$, the total cost function of the GSC can be written as $Z^c = IC^c + p.\ (E^c - cap)$. Similar the technique that we used in the previous section, the total cost function can be simplified to $Z^c = YT + \frac{X}{T} + p.\ (\hat{Y}T + \frac{\hat{X}}{T}) - p.\ cap$. Thus, it is easy to calculate the following equations.

$$T^* = \sqrt{\frac{X + p\hat{X}}{Y + p\hat{Y}}} \tag{81}$$

$$Z^{c*} = 2\sqrt{(Y + p\hat{Y})(X + p\hat{X})} + p.\ cap \tag{82}$$

The optimal values of integer variables can be found by the same method that used in the previous section. As a result, the multipliers of the retailers' replenishment cycle are:

Table 9
The computational results for each scenario of the non-coordinated GSC.

Decision Variables	Scenario number			
	1	2	3	4
$T_{4,r1}$	0.022	0.022	0.054	0.024
$T_{4,r2}$	0.017	0.017	0.036	0.018
$T_{4,r3}$	0.016	0.016	0.04	0.018
$T_{4,r4}$	0.023	0.023	0.064	0.025
$T_{3,d1}$	0.015	0.015	0.023	0.016
$T_{3,d2}$	0.016	0.016	0.026	0.017
$T_{2,m}$	0.018	0.025	0.003	0.018
$T_{1,s1}$	0.017	0.016	0.006	0.014
$T_{1,s2}$	0.017	0.017	0.007	0.015
$T_{1,s3}$	0.023	0.023	0.011	0.020
k_w	1	1	4	1
IC^n_4	30,367	30,268	32,226	29,476*
IC^n_3	34,439*	34,508	52,451	35,242
IC^n_2	55,159	52,938*	175,930	55,238
IC^n_1	24,230*	24,235	34,796	24,576
IC^n	144,195	141,948	295,403*	144,531
Z^n_4	30,367	30,499	−1,810,859*	29,476
Z^n_3	34,439	35,061	−15,178*	35,242
Z^n_2	55,159*	55,527	2,302,522	55,238
Z^n_1	24,230	24,847	−535,545*	24,576
Z^n	144,195	145,935	−59,061*	144,531
E^n_4	232	232	261	227*
E^n_3	556	553	371*	525
E^n_2	1918	2589	793*	1940
E^n_1	621	612	425*	552
E^n	3328	3986	1850*	3244
τ	–	1	–	–
p	–	–	3554	11
cap	1918	–	195	158,545
GNR	–	3986	–	–
u_{gov}	103,156	105,898	−26,185*	102,939

Table 10
The computational results for each scenario of the coordinated GSC.

Decision Variables	Scenario number			
	5	6	7	8
T	0.017	0.016	0.004	0.016
k_d	1	1	1	1
k_m	1	1	1	1
k_w	1	1	5	1
k_s	1	1	1	1
IC^c_4	32,075*	33,008	100,830	33,008
IC^c_3	1709*	1815	7251	1815
IC^c_2	22,926	22,077	21,925*	22,077
IC^c_1	11,310	10,645*	13,305	10,645*
IC^c	68,020	67,544*	143,311	67,544*
Z^c_4	32,075*	33,256	100,614	33,008
Z^c_3	1709*	2034	7658	1815
Z^c_2	22,926	23,687	22,514	22,077*
Z^c_1	11,310	11,121	13,198	10,645*
Z^c	68,020	70,098	143,985	67,544*
E^c_4	243*	249	718	249
E^c_3	206*	219	875	219
E^c_2	1711	1610	823*	1610
E^c_1	506	476*	595	476*
E^c	2665	2553*	3011	2553*
τ	–	1	–	–
p	–	–	1	1
cap	1711	–	234	12,657
GNR	–	2553	–	–
u_{gov}	54,139	53,805*	101,446	53,294*

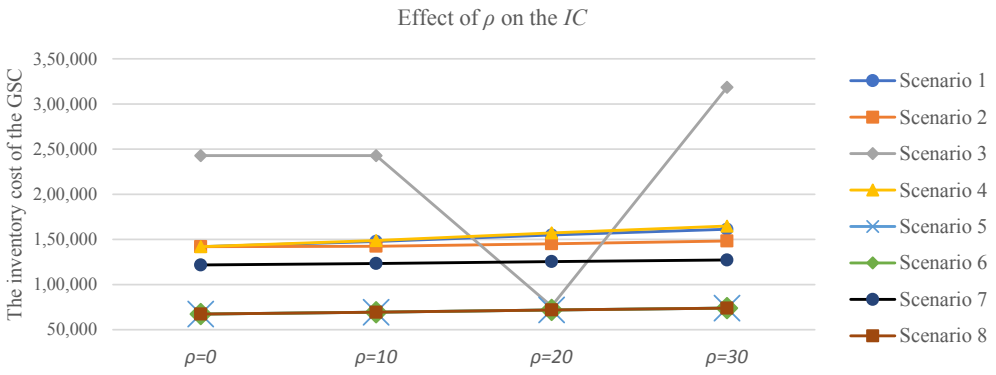

Fig. 4. The sensitivity of the optimal values of the inventory cost to the parameter ρ.

$$k_d^* = \sqrt{\frac{(\upsilon + p\hat{\upsilon})(\alpha_1 + p\hat{\alpha}_1)}{(\omega + p\hat{\omega})(\alpha_2 + p\hat{\alpha}_2)}} \tag{83}$$

$$k_m^* = \sqrt{\frac{(\varphi_2 + \frac{1}{k_w}\varphi_1 + p(\hat{\varphi}_2 + \frac{1}{k_w}\hat{\varphi}_1))(\gamma_3 + p\hat{\gamma}_3)}{(\gamma_2 + k_w\gamma_1 + p(\hat{\gamma}_2 + k_w\hat{\gamma}_1))(\sum_j A_{3,j} + pe^o_{3,j})}} \tag{84}$$

$$k_w^* = \sqrt{\frac{(\varphi_1 + p\hat{\varphi}_1)(\gamma_2 + p\hat{\gamma}_2)}{(\gamma_1 + p\hat{\gamma}_1)(\varphi_2 + p\hat{\varphi}_2)}} \tag{85}$$

$$k_s^* = \sqrt{\sum_j \frac{(h_w + pe^h_{2,m})(A_{1,j} + pe^o_{1,j})}{(h_{1,j} + pe^h_{1,j})(A_{2,m} + b_{1,j} + pe^t_{1,j})}} \tag{86}$$

5.8. The coordinated GSC under carbon offset regulation (Scenario 8)

The total cost of the GSC in this scenario is $Z^c = IC^c + p.(E^c - cap)^+$. It means, if the carbon emission of the GSC is more than a certain cap, $E^c > cap$, the total cost will be $Z^c = IC^c + p.(cap - E^c)^+$. And if the carbon emission is less than a cap, $E^c \leqslant cap$, the total cost will be $Z^c = IC^c$. The optimal values of the GSC in this scenario can be obtained in two cases by using the proposed algebraic method. when $E^c > cap$ the decision variables of the lower level problem can formulate as the carbon trade problem and when $E^c \leqslant cap$ the variables can formulate as the carbon cap problem. Consequently, the optimal values of the GSC in Scenario 8 are as follows.

$$T^* = \begin{cases} \sqrt{\frac{X}{Y}} & E^c \leqslant cap \\ \sqrt{\frac{X + p\hat{X}}{Y + p\hat{Y}}} & E^c > cap \end{cases} \tag{87}$$

$$k_d^* = \begin{cases} \sqrt{\frac{\upsilon\alpha_1}{\omega\alpha_2}} & E^c \leqslant cap \\ \sqrt{\frac{(\upsilon + p\hat{\upsilon})(\alpha_1 + p\hat{\alpha}_1)}{(\omega + p\hat{\omega})(\alpha_2 + p\hat{\alpha}_2)}} & E^c > cap \end{cases} \tag{88}$$

$$k_m^* = \begin{cases} \sqrt{\frac{(\varphi_2 + \frac{1}{k_w}\varphi_1)\gamma_3}{(\gamma_2 + k_w\gamma_1)A_{3,j}}} & E^c \leqslant cap \\ \sqrt{\frac{(\varphi_2 + \frac{1}{k_w}\varphi_1 + p(\hat{\varphi}_2 + \frac{1}{k_w}\hat{\varphi}_1))(\gamma_3 + p\hat{\gamma}_3)}{(\gamma_2 + k_w\gamma_1 + p(\hat{\gamma}_2 + k_w\hat{\gamma}_1))(A_{3,j} + pe^o_{3,j})}} & E^c > cap \end{cases} \tag{89}$$

$$k_w^* = \begin{cases} \sqrt{\frac{\gamma_2\varphi_1}{\gamma_1\varphi_2}} & E^c \leqslant cap \\ \sqrt{\frac{(\varphi_1 + p\hat{\varphi}_1)(\gamma_2 + p\hat{\gamma}_2)}{(\gamma_1 + p\hat{\gamma}_1)(\varphi_2 + p\hat{\varphi}_2)}} & E^c > cap \end{cases} \tag{90}$$

$$k_s^* = \begin{cases} \sqrt{\frac{A_{1,j}h_w}{h_{1,j}(A_{2,m} + b_{1,j})}} & E^c \leqslant cap \\ \sqrt{\frac{(h_w + pe^h_{2,m})(A_{1,j} + pe^o_{1,j})}{(h_{1,j} + pe^h_{1,j})(A_{2,m} + b_{1,j} + pe^t_{1,j})}} & E^c > cap \end{cases} \tag{91}$$

Based on the best response strategies of the models, we propose the following solution method for coordinated problems (Scenarios 5–8).

- ***Step 1.*** For a given value of governments' parameters and variables, calculate a continues value of k_s^*.
- Use Eq. (66) for the Scenario 5.
- Use Eq. (80) for the Scenario 6.
- Use Eq. (86) for the Scenario 7.
- Use Eq. (91) for the Scenario 8.
- ***Step 2.*** In each scenario calculate a continues values of k_w^*, k_m^*, k_d^* And compute replenishment cycle T^*.
- Use Eqs. (56),(60),(62),(64) for the Scenario 5.
- Use Eqs. (70),(74),(76),(78) for the Scenario 6.
- Use Eqs. (81)–(85) for the Scenario 7.
- Use Eqs. (87)–(91) for the Scenario 8.

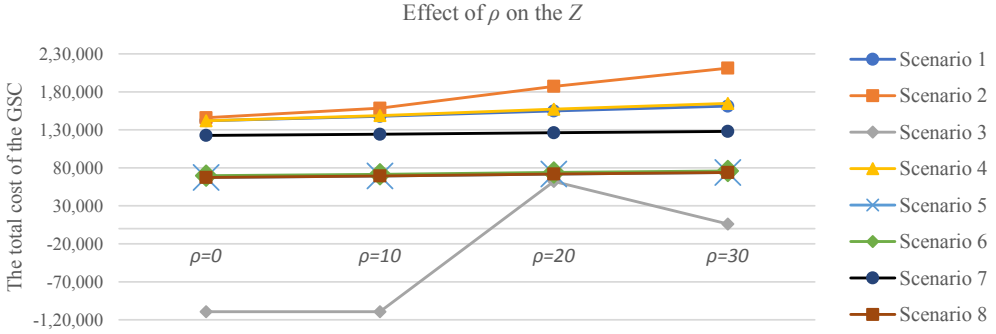

Fig. 5. The sensitivity of the optimal values of the total cost to the parameter ρ.

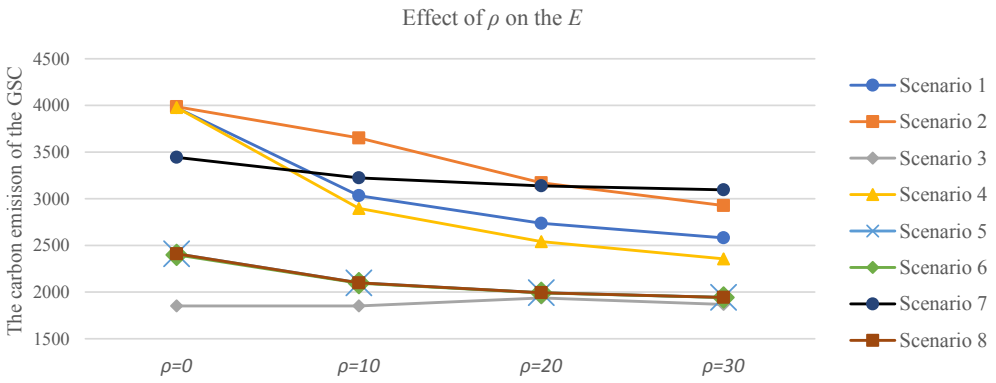

Fig. 6. The sensitivity of the optimal values of the carbon emission to the parameter ρ.

- ***Step 3.*** In each scenario, put the values of $k_s = \lceil k_s \rceil$, $k_s = \lfloor k_s \rfloor$, $k_w = \lceil k_w \rceil$, $k_w = \lfloor k_w \rfloor$, $k_m = \lceil k_m \rceil$, $k_m = \lfloor k_m \rfloor$, $k_d = \lceil k_d \rceil$, $k_d = \lfloor k_d \rfloor$ in the GSC problem and compute Z^c.
- ***Step 4.*** In each scenario, let k_s^*, k_w^*, k_m^*, k_d^* be the integer values that leading to a minimum Z^c.
- ***Step 5.*** Put the optimal values of the coordinated GSC in the government problem and use Baron solver through GAMS software to find the decision variables of the government and u_{gov}^*.

6. Numerical example

We illustrate the applicability of the mathematical models developed previously through the following numerical example. In practice, the input data for modeling the problem can obtain through several sources. Usually, the values of the parameters of the inventory model can be derived from the firms' formal financial statements. These statements record the firm's costs and revenues clearly and are available to the government to be audited. Besides, the carbon emissions of firms are measurable by using standards and tools that developed by several organizations such as GHG protocol, EPA, Carbon Trust and ISO 14064 (Benjaafar et al., 2013). There are also third parties that provide services for measurement of GHG emissions such as testing capabilities of a product, online emission measurements, emissions monitoring, evaporative emission testing, data acquisition and reporting, etc. The emission data needs to be reported to the government in order to meet the requirements. For example, the European firms that trade their carbon credit under the ETS system, are obligated to document and report their emissions (Ellerman, Convery, & De Perthuis, 2010). Therefore, the firms' financial and environmental information can be used by both GSC and government, to build an effective model to manage costs and carbon emissions. In this example, we consider a GSC consists of four retailers, two distributors, one manufacturer, and three suppliers. The input parameters for the retailers and distributors are presented in Tables 6 and 7, respectively.

In this example, the values of the manufacturer parameters are $S_m = 450$, $h_m = 15$, $P_m = 36{,}000$, $b_{2,m} = 20$, $A_m = 70$ and $h_w = 10$ and the carbon emission factors of the manufacturer are $e_{2,m}^o = 0.4$, $e_{2,m}^h = 0.3$, $e_{2,m}^t = 1.5$ and $e_{2,m}^p = 2$. Moreover, each unit of the product requires three types of raw materials that are supplied by three different suppliers. The consumption ratio of raw materials in a product is $\beta_{s1} = 2$, $\beta_{s2} = 2$ and $\beta_{s3} = 1$. The other input parameters of suppliers are presented in Table 8. Finally, the parameters of the government are $\rho = 5$ and $\Omega = 0.4$.

This example is formulated by the methods that described in Section 5 and was programmed in GAMS v24.1.2 software. The computational results of the discussed problem are presented in Tables 9 and 10 under non-coordinated and coordinated structures of the GSC.

From the results, we can compare the cost of the GSC among different scenarios. As it is evident, the inventory cost of the GSC under the coordinated structures is less than that in the non-coordinated ones. In Scenario 3 (non-coordinated GSC under the carbon trade scheme), the value of the GSC's total cost becomes negative. It means the GSC earn revenue more than its inventory cost by selling carbon credits. However, in the coordinated GSC the least total cost obtained at Scenario 8. Also, reviewing the cost of the GSC reveals that each regulation gives advantages for some members and disadvantages for some others. The lowest cost of the retailers, distributors, and suppliers of the non-coordinated GSC are obtained under the carbon trade scheme but the manufacturer's lowest cost is obtained under the carbon cap scheme. Moreover, in the coordinated GSC, retailers, and distributors reach least cost under the carbon cap scheme but the manufacturer and suppliers can reach their least cost under the carbon offset scheme.

From the environmental benefits perspective, the results show that the lowest carbon emission is obtained in Scenario 3 due to the financial incentives of the carbon trade system for carbon footprint reduction.

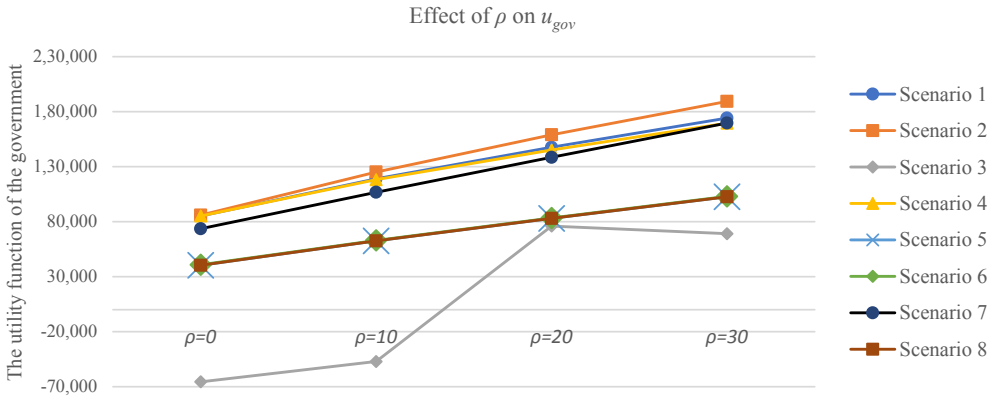

Fig. 7. The sensitivity of the optimal values of the utility function of the government to the parameter ρ.

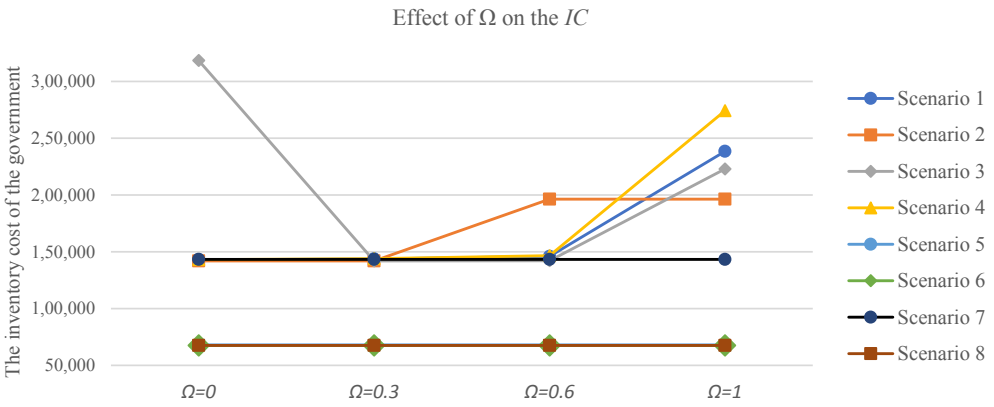

Fig. 8. The sensitivity of the optimal values of the inventory cost to the parameter Ω.

Also, the minimum amount of carbon emission in the coordinated scenarios is obtained under the carbon tax and carbon offset regulations. It can also be seen that in the most scenarios the carbon emission of the coordinated GSC is less than that in the non-coordinated GSC as well as cost. However, by the assumptions of this paper, the carbon trade regulation can be the most desirable for the government due to the minimum value of the u_{gov} in Scenario 3.

For further analysis, the sensitivity of the inventory cost, total cost, carbon emission, and utility function to the government's parameter ρ has been investigated. Figs. 4–6 show that by increasing ρ, the inventory cost and total cost of the GSC slightly increase in all scenarios except for Scenario 3. The cost of the GSC in Scenario 3 is more sensitive to the parameter ρ. Also, when the government's parameter ρ increases, the carbon emission of the GSC will decrease. It means when the government is more concerned about the environment than the economic aspects, he puts more pressure on the GSC for carbon reduction and as a result, the GSC incurs more cost. In addition, from Fig. 7, we can see that the utility function of the government is very sensitive to the parameter ρ. Thus, the government with right choice can achieve the desirable social welfare.

Moreover, the sensitivity analysis of the cost and emission of the GSC, and utility function of the government in accordance to the parameter Ω shown in Figs. 8–11. The results show that by increasing Ω; i.e., the government pays more attention to his revenue than GSC costs; the utility function of the government decreases. The cost function of the GSC is more sensitive to parameter Ω under the carbon tax scheme due to the existence of GNR on the government's objective function. By increasing Ω to its maximum level, the total cost of the GSC reaches its maximum acceptable value M_z, under Scenarios 2 and 6. In contrary, when Ω increases the carbon emissions decrease. However, the GSC's cost and emission are not sensitive to Ω under Scenarios 5, 7 and 8.

The effect of government's parameters on the replenishment cycle of the manufacturer is important because changes in this cycle will change the production quantity of the GSC. The sensitivity of the manufacturer's replenishment cycle $T_{2,m}$ in accordance with government's parameters ρ and Ω are shown in Figs. 12 and 13. It can be seen that both ρ and Ω have inverse relationship with the manufacturer's replenishment cycle in the non-coordinated GSC. However, these parameters have no effect on the manufacturer's replenishment cycle in the coordinated GSC.

We now investigate the sensitivity of inventory input parameters to the results. The demand, holding cost and ordering cost change from +25% to +100% and their effect on the cost and emission of the GSC and the government's utility function are determined as presented in Tables 11 and 12. We find that the cost and the carbon emission increase simultaneously in all scenarios when the market demand rises and consequently the government's utility function also increases. Furthermore, when the holding costs increase, the total cost of the GSC increases as expected and the utility function of the government increases too, but the emission of the GSC decreases. Also, increasing the ordering costs will increase the total cost, the utility function of the government and the carbon emission.

From the numerical example, the following managerial insights can be inferred.

- The results from different scenarios show that inventory decisions have an impact on the carbon emission of the GSC. Thus, a firm can reduce his carbon emission through operational adjustment instead of other costly methods.
- The members of the GSC can reduce their both inventory cost and their carbon emission by implementing a coordination mechanism for managing product flows. Consequently, cooperation helps both the government and the GSC to achieve their goals. However, the

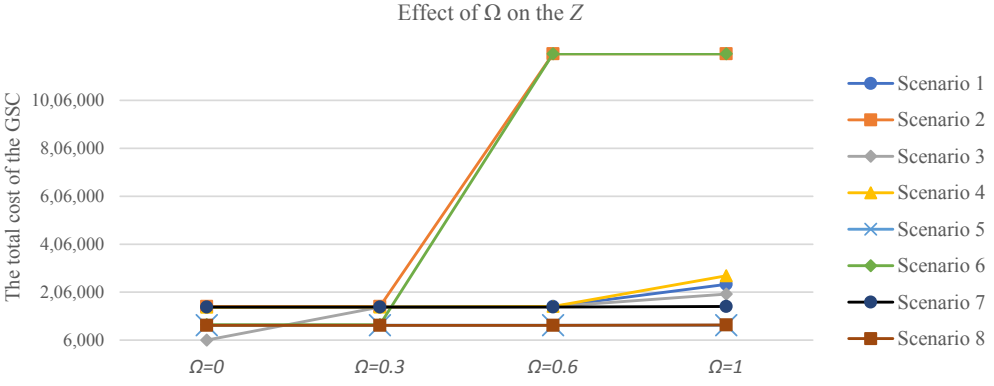

Fig. 9. The sensitivity of the optimal values of the total cost to the parameter Ω.

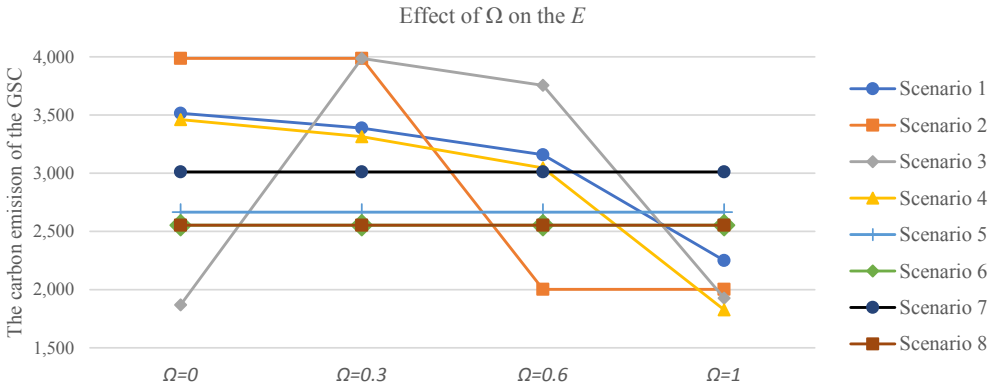

Fig. 10. The sensitivity of the optimal values of the carbon emission to the parameter Ω.

coordinated scheme may be difficult to implement in practice because it requires a decision maker who has information of all members.

- When the government increases the value of environmental importance factor ρ, the cost of the GSC will increase and the carbon emission will decrease. Thus the cost and carbon emission have an inverse relationship. Also, when the government increases the value of his revenue importance factor Ω, the GSC cost increase and as a result the emission decrease. Moreover, each regulation affects the cost and the carbon emission of each stage of the GSC differently.
- Among the four regulations that examined in this study, the carbon trade scheme can be more appropriate from the social welfare point of view. This result shows that governments may achieve their goals by setting incentive policies.
- By changing the government's policies, the appropriate regulation can be different. If only the environmental benefits are considered by the government, the schemes such as carbon tax and carbon offset may be effective as well as carbon trade scheme. But the governments should consider that these schemes are kind of a command-and-control policy and deviate firms from their optimal solutions and increase their cost and dissatisfaction. Besides, if the government only considers the GNR, the carbon tax policy may be more effective and the optimal solution may be different.
- The sensitivity analysis of the model to the government' environmental importance factor shows that the total cost of the GSC, the carbon emission and social welfare are affected by government regulations and decisions. Thus, the government can achieve the optimal trade-off between the carbon emission and the profit of firms by applying an appropriate regulation and adjusting the optimal parameters and variables.
- The sensitivity analysis of the model to the inventory parameters shows that the carbon emission of the GSC has a direct relation with demand and ordering cost but has an inverse relationship with the inventory holding cost. In addition, the utility function of the government has a direct relationship with parameters of the inventory model.

7. Conclusion

The purpose of this study was to contribute to the field of inventory management of a multi-stage GSC under carbon emission regulations. This paper used to determine the importance of the inventory decisions for compliance the GSC with carbon regulations and also analyzing the effect of these regulations on the cost and carbon emission. Therefore, a mathematical model is developed for inventory cost and carbon emission of a four-echelon GSC based on the non-coordinated and coordinated decision-making structures. In addition, four different regulations associated with controlling carbon emission have examined in the model of the GSC. Thus, eight scenarios are developed based on these regulations and the structure of the GSC. Each scenario modeled as a Stackelberg game, where at first the government (leader) as a more powerful player, set a regulation and based on that, determines a certain cap, carbon tax or carbon price to maximize SW. Second, the GSC (follower) determines the replenishment cycle of each stage and the production quantity. This game expressed as a bi-level MINLP. Then the problems of the non-coordinated GSC reformulated to single-level problems by replacing the KKT condition of the lower level problems. In addition, an algebraic method presented for solving the problems of the coordinated GSC.

The findings of this study from the numerical example highlight that inventory decisions have an influence on the carbon emission of the GSC and consequently, operational adjustment can be an effective way for carbon reduction. Moreover, the firms in a GSC can reduce both their cost and carbon emission by using a coordination mechanism in

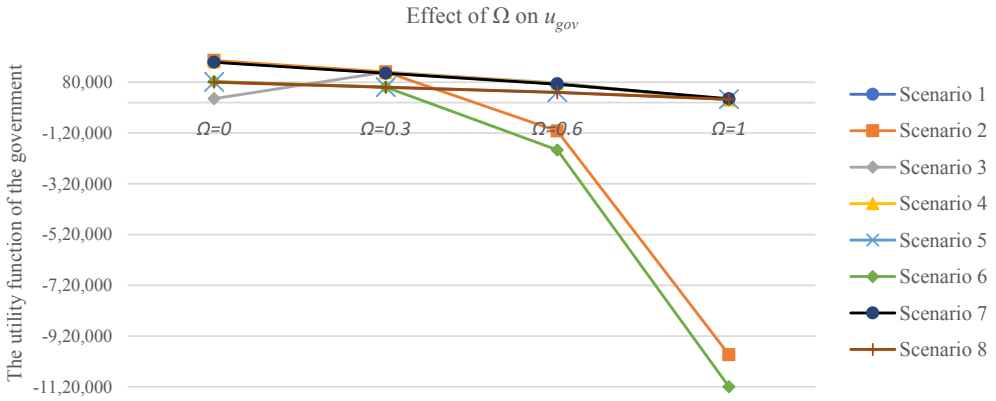

Fig. 11. The sensitivity of the optimal values of the utility function of the government to the parameter Ω.

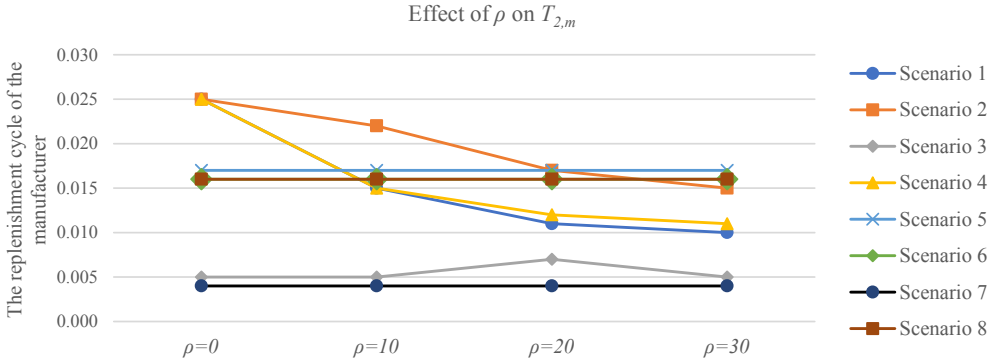

Fig. 12. The sensitivity of the manufacturer's replenishment cycle to the parameter ρ.

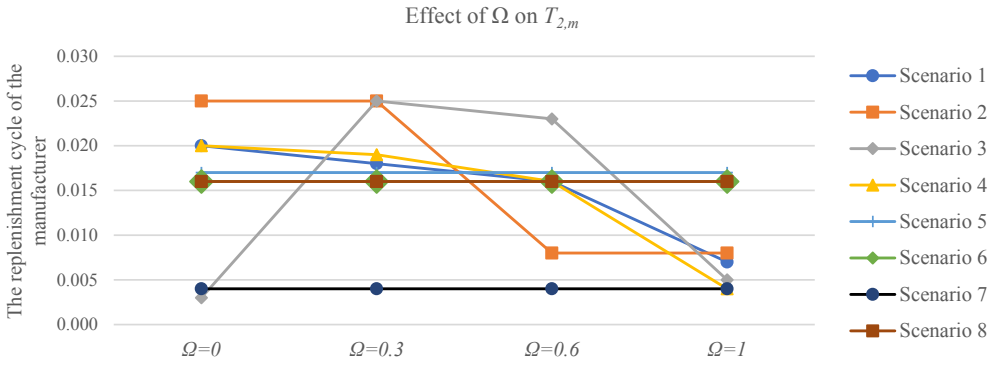

Fig. 13. The sensitivity of the manufacturer's replenishment cycle to the parameter Ω.

Table 11
The sensitivity of the results to the input parameters in the non-coordinated GSC.

	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
Changes of $D_{i,j}$	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}
+25%	161,215	3720	115,331	163,160	4457	118,397	160,341	4457	118,489	161,591	3627	115,089
+50%	180,243	4160	128,944	182,418	4983	132,372	179,423	4983	132,568	180,663	4055	128,674
+75%	201,518	4651	144,164	203,949	5571	147,996	200,758	5571	148,310	201,987	4534	143,861
+100%	225,303	5200	161,180	228,021	6229	165,464	224,612	6229	165,910	225,829	5069	160,842
Changes of $h_{i,j}$	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}
+25%	160,486	3256	112,569	162,496	3787	114,918	−86,245	1851	−42,490	160,796	3182	112,385
+50%	178,828	3201	123,301	181,077	3626	125,326	−54,845	1840	−23,705	179,132	3131	123,136
+75%	199,450	3166	135,499	201,911	3503	137,262	−19,098	1840	−2,256	199,768	3097	135,346
+100%	222,605	3153	149,329	225,259	3419	150,884	222,786	3419	150,768	222,956	3082	149,185
Changes of $A_{i,j}$	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}	Z^n	E^n	u_{gov}
+25%	155,429	3356	110,037	157,164	4021	112,797	154,490	4021	112,801	155,765	3272	109,818
+50%	168,188	3406	117,945	169,933	4080	120,727	−78,710	1852	−37,966	168,539	3318	117,714
+75%	182,659	3482	127,004	184,430	4165	129,815	−57,625	1852	−25,313	183,039	3385	126,751
+100%	199,051	3584	137,352	200,866	4279	140,202	−31,419	1842	−9,642	199,473	3477	137,069

inventory decisions. In addition, the inventory cost and the carbon emission of the GSC have inverse relations and the government can trade-off the costs and carbon emissions by setting appropriate regulation and parameters. Among the different regulations that examined, the carbon trade scheme can be more effective from the point of view of both GSC and SW. However, the results may differ by changing the government policies. For instance, if the government seeks to maximize his revenue the carbon tax policy may be more effective.

Finally, we propose that future studies can consider complex assumptions of inventory management such as deteriorating products and delayed payment during demand uncertainty. In addition, the developed models can be expanded by engaging the concepts of rewards-driven systems and maintenance scheduling with GSCM (see Duan, Deng, Gharaei, Wu, & Wang, 2018; Gharaei, Naderi, & Mohammadi, 2015). Besides, this study considered a Stackelberg game between the GSC and the government. One may consider other games such as cooperation for further study. Besides, the impact of other regulations of the government on the inventory cost is an interesting future research area.

Table 12
The sensitivity of the results to the input parameters in the coordinated GSC.

	Scenario 5			Scenario 6			Scenario 7			Scenario 8		
Changes of $D_{i,j}$	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}
+25%	76,074	2466	57,973	78,586	2459	58,465	137,877	3694	101,197	76,074	2466	57,973
+50%	85,051	2757	64,814	87,860	2750	65,364	154,307	4130	113,235	85,051	2757	64,814
+75%	95,087	3082	72,463	98,228	3074	73,078	172,675	4618	126,693	95,087	3082	72,463
+100%	106,309	3446	81,014	109,820	3437	81,703	193,212	5163	141,741	106,309	3446	81,014
Changes of $h_{i,j}$	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}
+25%	75,735	2118	56,031	77,881	2114	56,455	137,213	3202	98,336	75,735	2118	56,031
+50%	84,425	2039	60,852	86,483	2037	61,259	153,035	3118	107,410	84,425	2039	60,852
+75%	94,217	1971	66,386	96,199	1970	66,780	170,835	3056	117,779	94,217	1971	66,386
+100%	105,225	1916	72,715	107,147	1915	73,098	190,825	3018	129,586	105,225	1916	72,715
Changes of $A_{i,j}$	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}	Z^c	E^c	u_{gov}
+25%	75,737	2332	57,104	78,123	2325	57,570	136,968	3447	99,418	75,737	2332	57,104
+50%	84,380	2485	63,055	86,931	2477	63,552	152,487	3627	109,628	84,380	2485	63,055
+75%	94,080	2667	69,785	96,826	2657	70,317	169,932	3847	121,197	94,080	2667	69,785
+100%	104,957	2881	77,379	107,932	2868	77,954	189,520	4112	134,272	104,957	2881	77,379

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Appendix A

The IC^n is convex when the inventory cost of each stage of the GSC be convex.

The second derivation of the inventory cost function of retailers is calculated as follows:

$$\frac{\partial^2 IC_4^n}{\partial T_{4,j}^2} = \sum_{j=r1}^{R} \frac{2A_{4,j}}{T_{4,j}^3} > 0 \tag{A.1}$$

The second derivation of the inventory cost function of the retailers is more than zero, as a result IC_4^n is convex. The second derivation of the inventory cost function of distributors is calculated as follows:

$$\frac{\partial^2 IC_3^n}{\partial T_{3,j}^2} = \sum_{j=d1}^{D} \frac{2A_{3,j}}{T_{3,j}^3} > 0 \tag{A.2}$$

The above equation shows IC_3^n is convex. The inventory cost function of the manufacture contains two decision variables ($T_{2,m}$, k_w). The hessian matrix of IC_2^n is calculated as follows:

$$H_{IC_2^n} = \begin{vmatrix} \frac{2S_m}{T_{2,m}^3} + \frac{2A_{2,m}}{k_w T_{2,m}^3} & \frac{A_{2,m}}{k_w^2 T_{2,m}^2} + h_w \sum_{s=s1}^{S} (\frac{\beta_s D_{2,m}}{2}) \\ \frac{A_{2,m}}{k_w^2 T_{2,m}^2} + h_w \sum_{s=s1}^{S} (\frac{\beta_s D_{2,m}}{2}) & \frac{2A_{2,m}}{k_w^3 T_{2,m}} \end{vmatrix} > 0 \tag{A.3}$$

The inventory cost function of the manufacturer is convex only if:

$$(\frac{2S_m}{T_{2,m}^3} + \frac{2A_{2,m}}{k_w T_{2,m}^3})(\frac{2A_{2,m}}{k_w^3 T_{2,m}}) - (\frac{A_{2,m}}{k_w^2 T_{2,m}^2} + h_w \sum_{s=s1}^{S} (\frac{\beta_s D_{2,m}}{2}))^2 > 0 \tag{A.4}$$

The second derivation of the inventory cost function of suppliers is calculated as follows:

$$\frac{\partial^2 IC_1^n}{\partial T_{1,j}^2} = \sum_{s=s1}^{S} \frac{2A_{1,j}}{T_{1,j}^3} > 0 \tag{A.5}$$

Given that the inventory cost of each stage of the GSC is convex, as a result, the Eq. (22) is convex.

Appendix B

The E^n is convex when the carbon emission of each stage of the GSC be convex.

The second derivation of the carbon emission function of retailers is calculated as follows:

$$\frac{\partial^2 E_4^n}{\partial T_{4,j}^2} = \sum_{j=r1}^{R} \frac{2e_{4,j}^o}{T_{4,j}^3} > 0 \tag{B.1}$$

The second derivation of the inventory cost function of the retailers is more than zero, as a result E_4^n is convex. The second derivation of the carbon emission function of distributors is calculated as follows:

$$\frac{\partial^2 E_3^n}{\partial T_{3,j}^2} = \sum_{j=d1}^{D} \frac{2e_{3,j}^o}{T_{3,j}^3} > 0 \tag{B.2}$$

The Eq. (B.2) shows E_3^n is convex. The carbon emission function of the manufacture is convex due to the following equation.

$$\frac{\partial^2 E_2^n}{\partial T_{2,m}^2} = \frac{2e_{2,m}^o}{T_{2,m}^3} > 0 \tag{B.3}$$

The second derivation of the carbon emission function of suppliers is calculated as follows:

$$\frac{\partial^2 E_1^n}{\partial T_{1,j}^2} = \sum_{s=s1}^{S} \frac{2e_{1,j}^o}{T_{1,j}^3} > 0 \tag{B.4}$$

Given that the carbon emission of each stage of the GSC is convex, as a result, the Eq. (23) is convex.

Appendix C

$$\gamma_1 = \sum_j (h_w \beta_s D_m + h_{1,j} k_s \beta_s D_m) = \sum_j (\beta_s D_m (h_w + h_{1,j} k_s)) \tag{C.1}$$

$$\gamma_2 = \sum_j (\frac{h_{2,m} D_m^2}{P_m} + h_{2,m} D_m + h_w \beta_s D_m (\frac{D_m}{P_m} - 1)) \tag{C.2}$$

$$\gamma_3 = D_m \sum_j (h_{3,j} - h_{2,m}) \tag{C.3}$$

$$\omega = \gamma_3 + k_m (\gamma_2 + k_w \gamma_1) \tag{C.4}$$

$$\alpha_1 = D_m \sum_j (h_{4,j} - h_{3,j}) \tag{C.5}$$

$$Y = \frac{k_d \omega + \alpha_1}{2} \tag{C.6}$$

$$\varphi_1 = \sum_j (A_{2,m} + b_{1,j} + \frac{A_{1,j}}{k_s}) \tag{C.7}$$

$$\varphi_2 = S_m + b_{2,m} \tag{C.8}$$

$$\upsilon = \sum_j A_{3,j} + \frac{1}{k_m} (\varphi_2 + \frac{1}{k_w} \varphi_1) \tag{C.9}$$

$$\alpha_2 = \sum_j (A_{4,j} + b_{3,j}) \tag{C.10}$$

$$X = \frac{\upsilon}{k_d} + \alpha_2 \tag{C.11}$$

Appendix D

$$\hat{\gamma}_1 = \sum_j (\beta_s D_m (e_{2,m}^h + e_{1,j}^h k_s)) \tag{D.1}$$

$$\hat{\gamma}_2 = e_{2,m}^h D_m (\frac{D_m}{P_m} + 1) + e_{2,m}^h \beta_s D_m (\frac{D_m}{P_m} - 1) + 2e_{2,m}^p D_m \tag{D.2}$$

$$\hat{\gamma}_3 = D_m \sum_J (e_{3,j}^h - e_{2,m}^h) \tag{D.3}$$

$$\hat{\omega} = \hat{\gamma}_3 + k_m (\hat{\gamma}_2 + k_w \hat{\gamma}_1) \tag{D.4}$$

$$\hat{\alpha}_1 = D_m \sum_j (e_{4,j}^h - e_{3,j}^h) \tag{D.5}$$

$$\hat{Y} = \frac{k_d \hat{\omega} + \hat{\alpha}_1}{2} \tag{D.6}$$

$$\hat{\varphi}_1 = \sum_j (e^t_{1,j} + \frac{e^o_{1,j}}{k_s}) \tag{D.7}$$

$$\hat{\varphi}_2 = e^o_{2,m} + e^t_{2,m} \tag{D.8}$$

$$\hat{\upsilon} = \sum_j e^o_{3,j} + \frac{1}{k_m}(\hat{\varphi}_2 + \frac{1}{k_w}\hat{\varphi}_1) \tag{D.9}$$

$$\hat{\alpha}_2 = \sum_j (e^o_{4,j} + e^t_{3,j}) \tag{D.10}$$

$$\hat{X} = \frac{\hat{\upsilon}}{k_d} + \hat{\alpha}_2 \tag{D.11}$$

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